RESULTS OF LABORATORY TESTING

The results from hundreds of lab tests of the nine LED signals are presented in this section of the report. These results will be summarized in two parts, based on the basic construction of the signals and operating similarities,

1. summary of results for the two 12 inch red crossing signals that did not have a power supply (NPS#1 and NPS#4),
2. summary of results for the four 12 inch red crossing signals that did have a power supply (WPS#2, WPS#3, WPS#5, and WPS#6),

Immediately following these two summaries are detailed results from each of the nine LED signals, as well as results from a small number of tests of a single 12 inch, red, incandescent crossing signal. Plots for the data collected in the lab are attached in the Appendix.

Summary of Results for 12 Inch Red Crossing Signals without Power Supplies

Two of the 12 inch red crossing signals that were tested did not use a power supply, NPS#1 and NPS#4. These signals are intended to be connected directly to the nominally 10 to 12 volt battery pack commonly found at crossings. Figure 11 summarizes the results from tests of these signals with 100% of the elements active at supply voltages ranging from 9 to 13 volts or more. Figure 12 summarizes the results from tests of these signals with different percentages of the elements active at a supply voltage of 10.5 volts. Three important observations about LED signals that do not use power supplies can be drawn from these two figures:

- there is a threshold supply voltage below which the signals have no light output,
- above this threshold voltage the maximum light intensity is a strong, fairly linear function of the supply voltage, and
- the maximum light intensity is essentially proportional to the number of active LED elements across the wide range tested (20% to 100% active).

As will be shown in later results, both of these signals exhibited a fairly constant relationship between the maximum light intensity and the current draw during all tests. For the NPS#1 signal (which uses fairly old technology), this constant is approximately 125 to 150 candela/amp. The NPS#4 signal had a much better light efficiency at roughly 700 to 900 candela/amp.

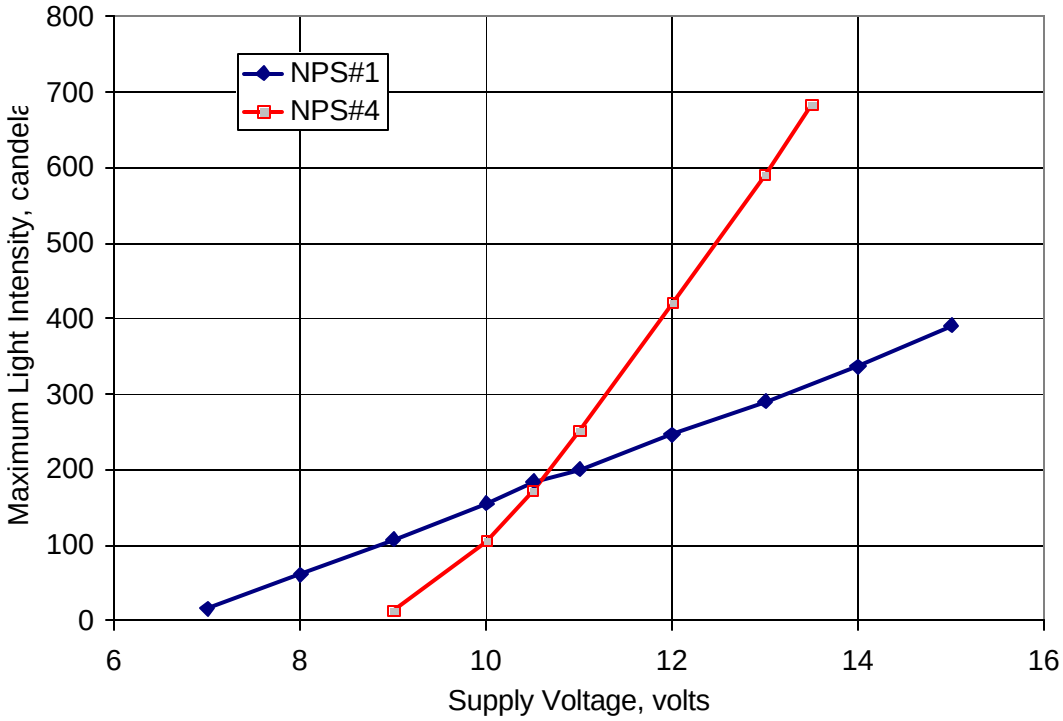

Figure 11. Maximum Light Intensity from NPS#1 and NPS#4 Signals with Different Supply Voltages.

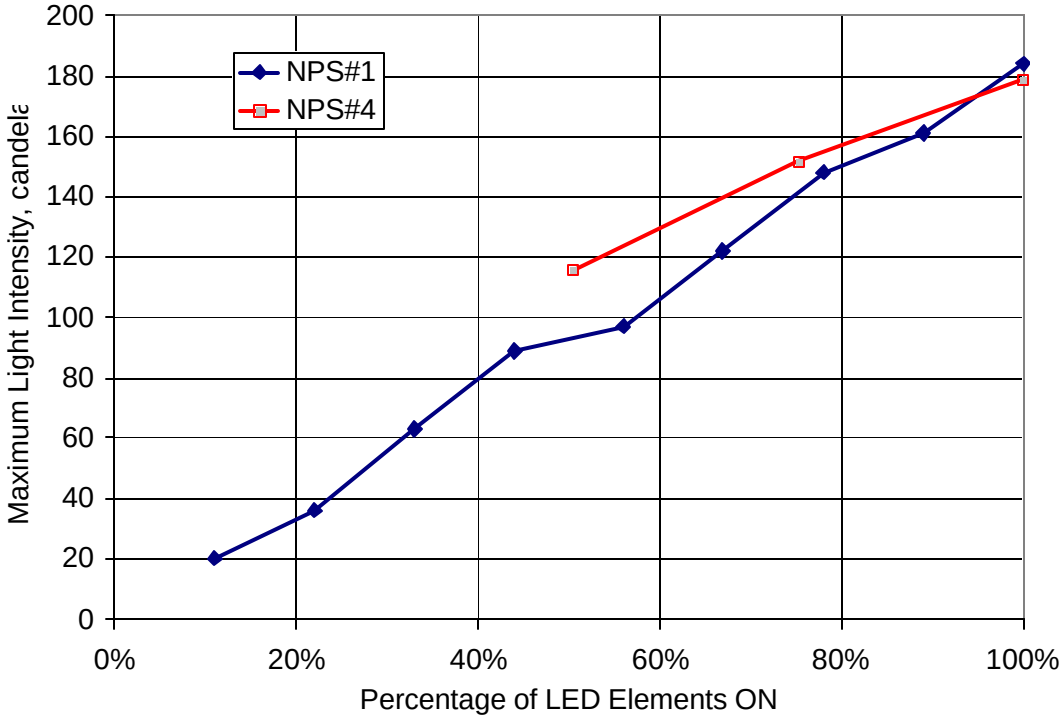

Figure 12. Maximum Light Intensity from NPS#1 and NPS#4 Signals with Different Percentages of Active Elements.

Summary of Results for 12 Inch Red Crossing Signals with Power Supplies

Four of the 12 inch red crossing signals that were tested used a power supply to regulate the current supplied to the LEDs (WPS#2, WPS#3, WPS#5 and WPS#6). These signals are clearly intended maintain a relatively constant light output over a fairly wide range of battery supply voltages. Figure 13 summarizes the results from tests of these signals with 100% of the elements active at supply voltages ranging from 7.5 to 13 volts or more. Figure 14 summarizes the results from tests of two of these signals (WPS#2 and WPS#3) with different percentages of the elements open-circuited at a supply voltage of 10.5 volts. Two important observations about LED signals that use power supplies or regulators can be drawn from these two figures:

1. above a threshold voltage (typically 9 volts), the maximum light intensity is not a strong function of the supply voltage, and
2. the maximum light intensity is not a strong function of the number of open-circuited LED elements.

As will be shown in later results, all four of these signals exhibited a fairly constant relationship between the maximum light intensity and the power consumption during all tests. These ratios ranged from 12 to 15 candela/watt for the WPS#5 signal up to about 60 to 70 candela/watt for the WPS#2 signal.

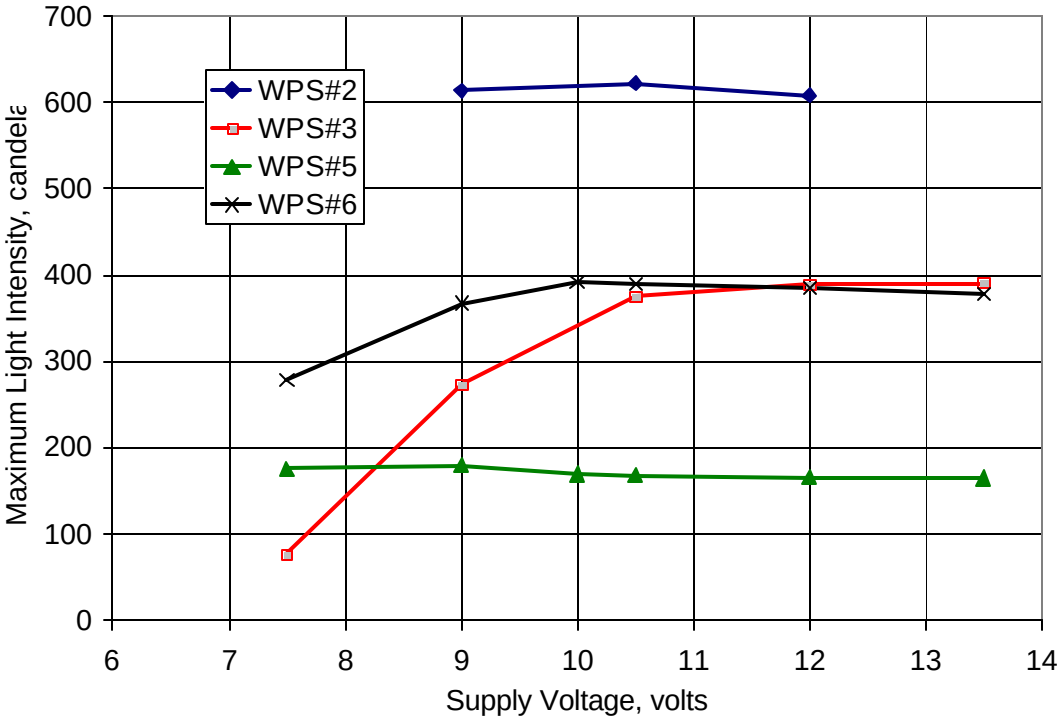

Figure 13. Maximum Light Intensity from WPS#2, WPS#3, WPS#5 and WPS#6 Signals with Different Supply Voltages.

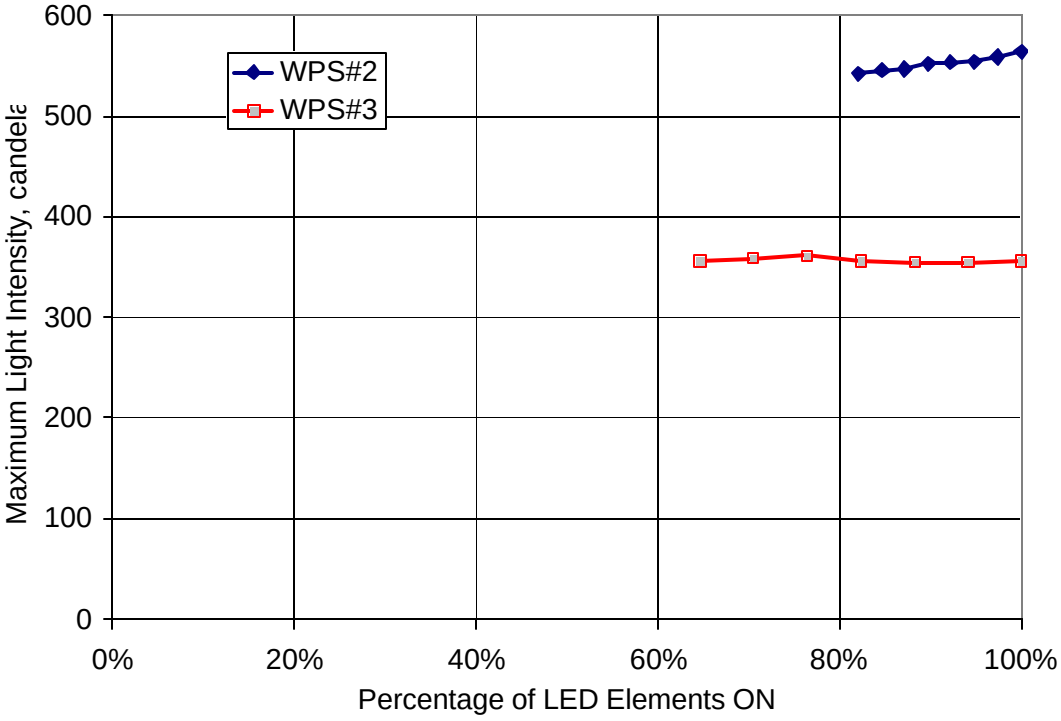

Figure 14. Maximum Light Intensity from WPS#2 and WPS#3 Signals with Different Percentages of Active Elements.

Data from Incandescent signal

A limited amount of data was collected from the incandescent signal purchased from Western Cullen-Hayes along with the aluminum signal housing. This unit was supplied with a 25 watt incandescent bulb and a 30/15 red lens. Figures A0.1 through A0.4 of the appendix show the effects of varying voltage in the range of 9.0 volts to 13.5 volts with the incandescent signal. Table 11 summarizes the maximum light intensity responses, which are significantly larger than any of the responses from the 12 inch red LED signals. The incandescent crossing signal has a distinct, very bright "hot spot" in the 0 degree, on-axis position. However, as the data in the appendix show, the light intensity drops rapidly as the signal is viewed in anything other than the horizontal plane. This observation was corroborated in the field tests conducted during the Transport Canada study. The incandescent signal is easily visible from large distances when viewed directly on-axis, but was significantly less visibly when viewed off-axis.

Table 11. Results from incandescent signal with varying voltage input.

Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)
9.0	1166	2.30	20.7
10.5	1889	2.50	26.3
12.0	2802	2.69	32.3
13.5	3923	2.88	38.8

Figure 15 shows the chromaticity results from the same tests shown in Table 11. The results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. There is a small, but definite trend towards a more red (larger x value), and less green (lower y value) color as the voltage is increased. Most of the LED signals did not exhibit this color shift trend as a function of supply voltage.

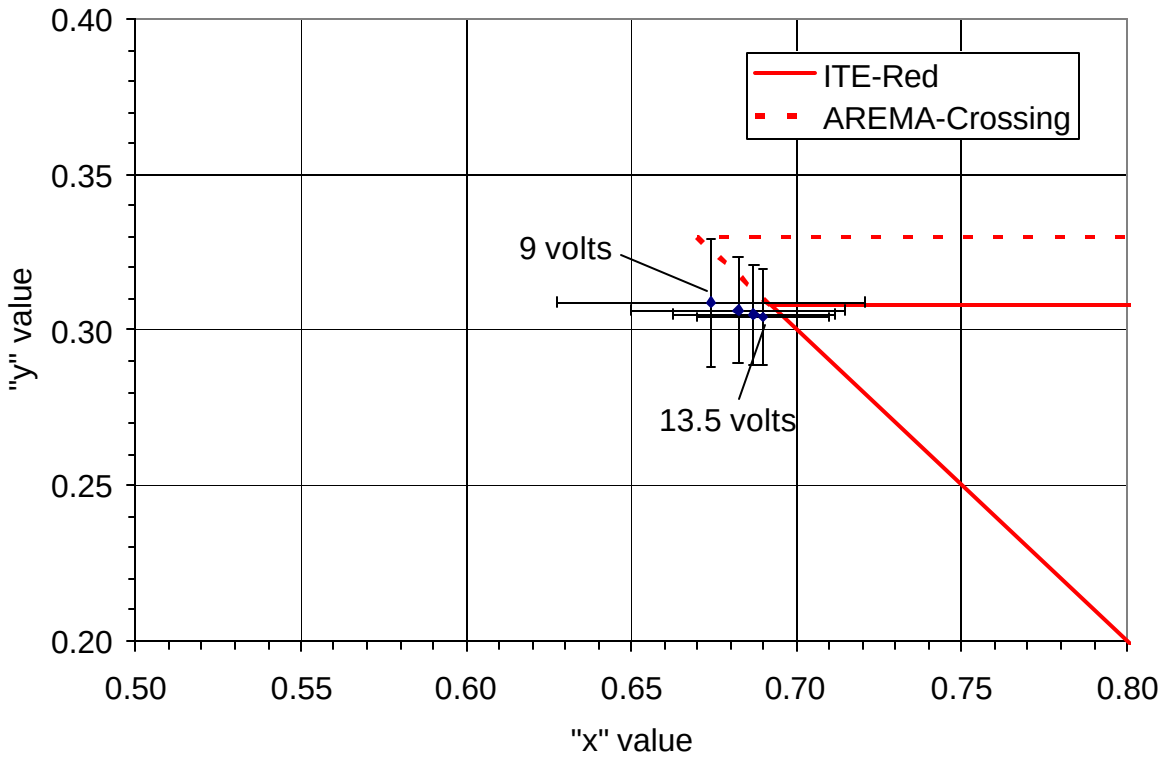

Figure 15. Chromaticity results from incandescent signal with varying voltage input.

Data from Aurora signal (NPS#1)

The first twelve inch rail crossing signal tested is the Aurora unit purchased from Western Cullen-Hayes. No power supply (NPS) is used with this signal - the LEDs are directly connected to AC or DC power. The circuit configuration for this signal is shown in Figure 16. This signal (referred to as NPS#1 in this report) has 72 sets of three LEDs arranged in a series circuit, for a total of 216 visible elements.

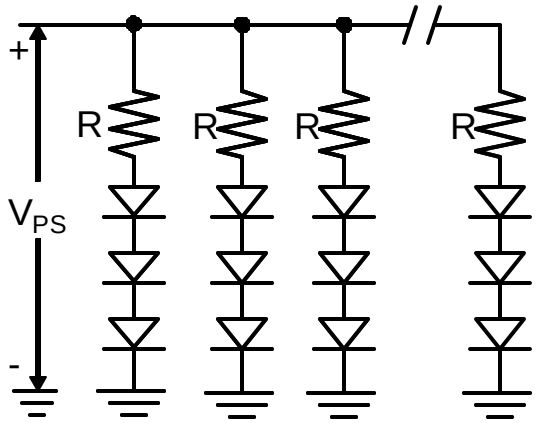

Figure 16. LED circuit configuration for NPS#1 signal.

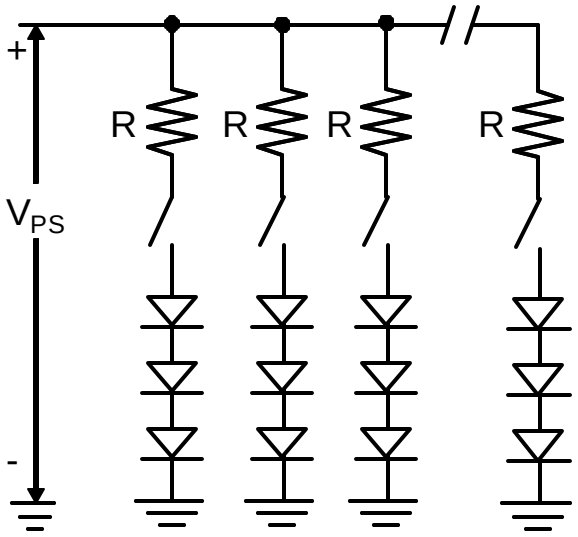

Figure 17. NPS#1 signal configured for open-circuiting.

Figures A1.1.1 through A1.1.10 of the appendix show the effects of varying voltage in the range of 7.0 volts to 15.0 volts with 100% of the LED elements active. Data from these figures is summarized in Table 12 and Figure 18. The light output from this signal is a strong function of the voltage, with maximum outputs ranging from 390 candela at 15.0 volts to 16 candela at 7.0 volts. The maximum output at the nominal 10.5 volts is approximately 184 candela. This value is fairly close to the nominal 160 candela rating of this light. As shown in Table 12, supply currents ranged from 0.13 amps at 7.0 volts to 2.52 amps at 15 volts with 1.11 amps at the nominal 10.5 volt input. Power consumption ranged from 0.9 watts at 7.0 volts to 21.8 watts at 15 volts with 13.2 watts at the nominal 10.5 volt input. The light-

current efficiency is relatively constant at 133 to 146 candela/amp at all but the lowest supply voltage.

Table 12. Results from NPS#1 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Current Efficiency (candela/amp)
7.0	16	0.13	0.9	126
8.0	60	0.42	3.4	142
9.0	107	0.76	6.8	141
10.0	155	1.11	11.1	139
10.5	184	1.26	13.2	146
11.0	200	1.46	16.1	137
12.0	245	1.82	21.8	135
13.0	290	2.17	28.2	134
14.0	336	2.52	35.3	133
15.0	390	2.87	43.1	136

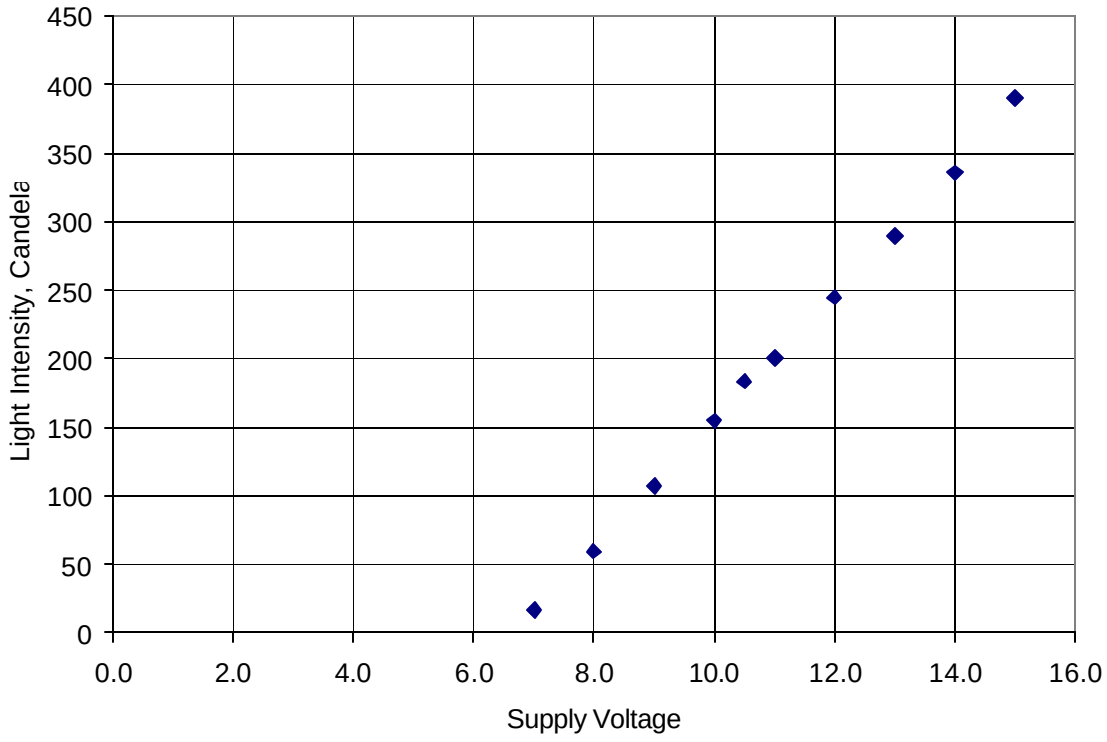

Figure 18. Maximum light intensity from NPS#1 with varying voltage input.

Figure 19 shows the chromaticity results from the same tests shown in Figure 18. All of the results (except for those at 7.0 volts) show very similar color values clustered near the

edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. The color shift at 7.0 volts is closely related to the low level of light intensity (only 16 candela). There is no apparent color shift with input voltage with the NPS#1 signal.

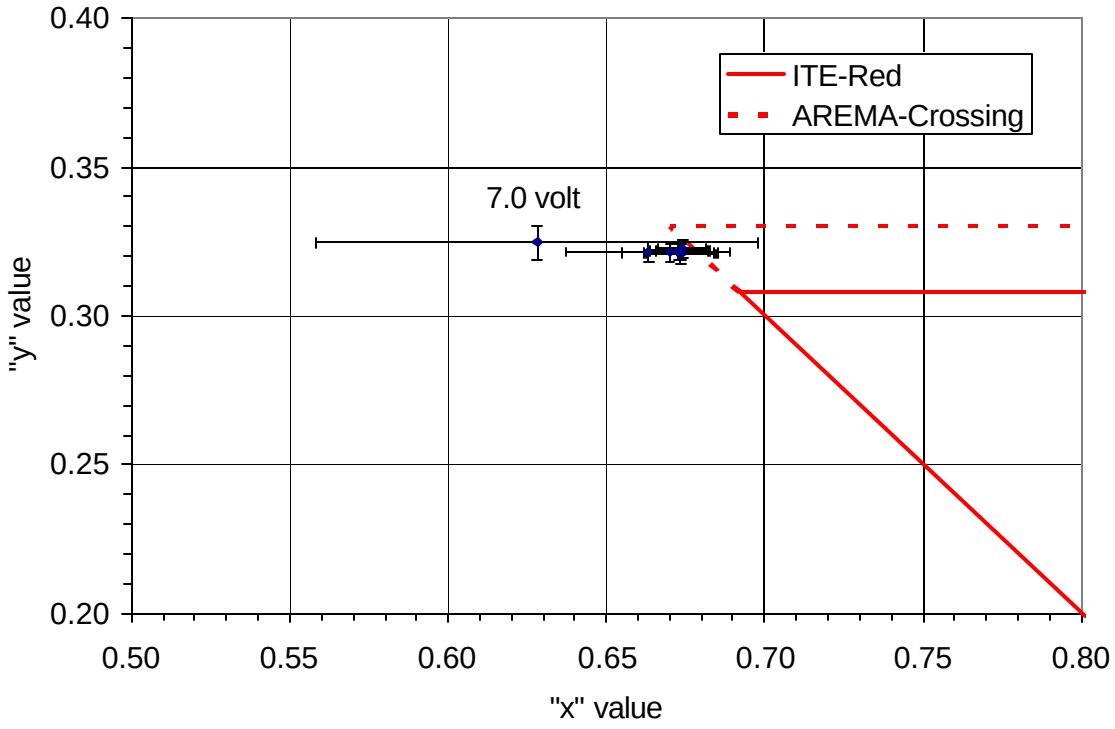

Figure 19. Chromaticity results from NPS#1 with varying voltage input.

Figures A1.2.1 through A.1.2.9 of the appendix show the effects of varying the number of active LED elements from 100% to 11% at a constant 10.5 volts. Table 13 and Figure 20 summarize these results. The light output from the NPS#1 signal is a strong function of the number of active elements, with maximum outputs ranging from 184 candela at 100% (216 elements) to 20 candela at 11% (24 elements). Supply currents ranged from 1.26 amps at 100% (216 elements) to 0.15 amps at 11% (24 elements). Power consumption ranged from 13.2 watts at 100% (216 elements) to 1.6 watts at 11% (24 elements). These results show a fairly linear relationship between the number of active LED elements and the maximum light intensity output. There is also a fairly constant relationship between the supply current and the maximum light intensity output of between 125 and 146 candela/amp.

Table 13. Results from NPS#1 at 10.5 volts.

Percentage of LEDs ON	Portion of Signal ON/OFF	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Current Efficiency (candela/amp)
100%	FFF	184	1.26	13.2	146
89%	FBF	161	1.13	11.9	143
78%	D7F	148	1.00	10.5	148
67%	FEC	122	0.86	9.0	141
56%	F93	97	0.72	7.6	135
44%	D6C	89	0.58	6.1	153
33%	D13	63	0.44	4.6	144
22%	F80	36	0.29	3.0	125
11%	D02	20	0.15	1.6	136

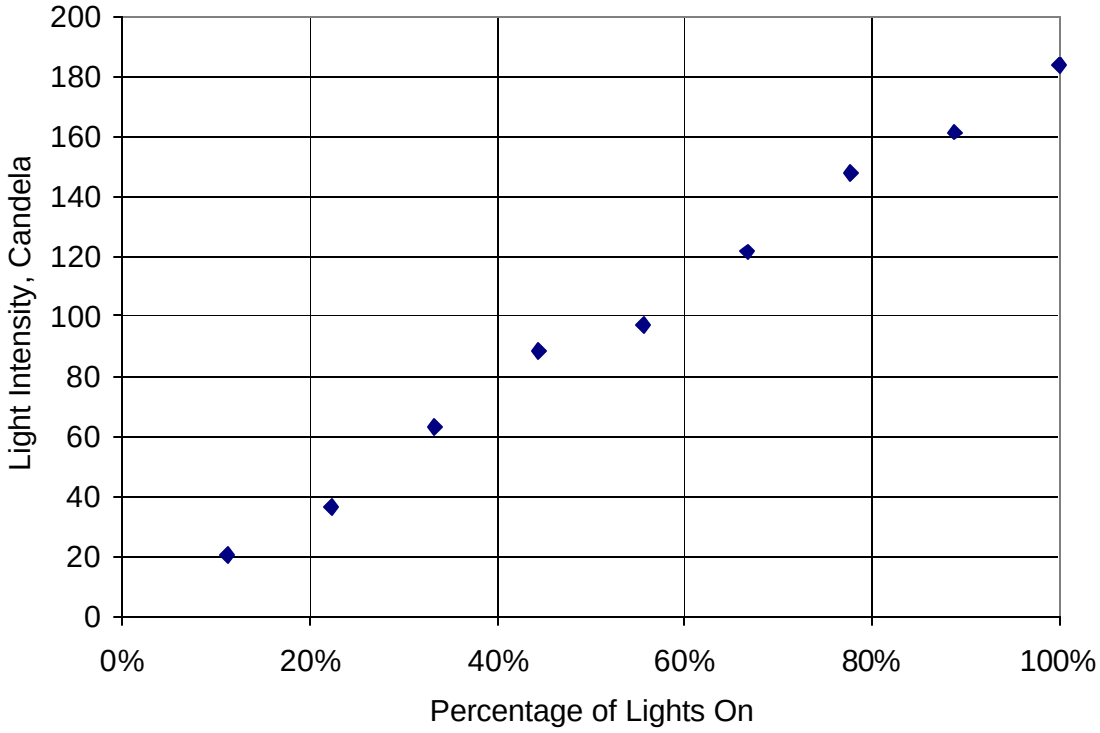

Figure 20. Maximum light intensity from NPS#1 at 10.5 volts.

Figure 21 shows the chromaticity results from the same tests shown in Figure 20. There is more scatter in the color measurements shown in this figure than in any other results of this report. However, there is no correlation to the color values and the percentage of lights

on. The data are essentially randomly distributed. Since this data was taken during one of the earliest tests conducted during the project, there may have been a testing error.

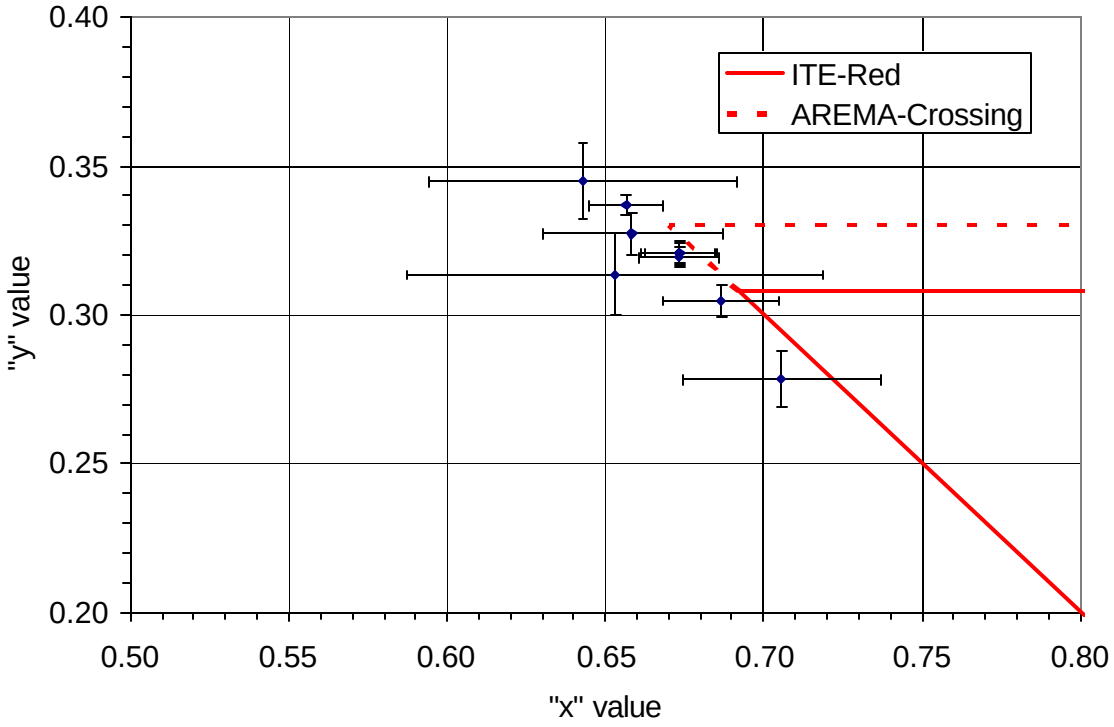

Figure 21. Chromaticity results from NPS#1 at 10.5 volts.

Figures A1.3.1 through A.1.5.10 of the appendix show the effects of varying the voltage in the range of 7.0 volts to 15.0 volts with 67% (144) of the LED elements active. Three different patterns of ON/OFF elements (FD3, FEC, and D3F) are shown in Figure 22.

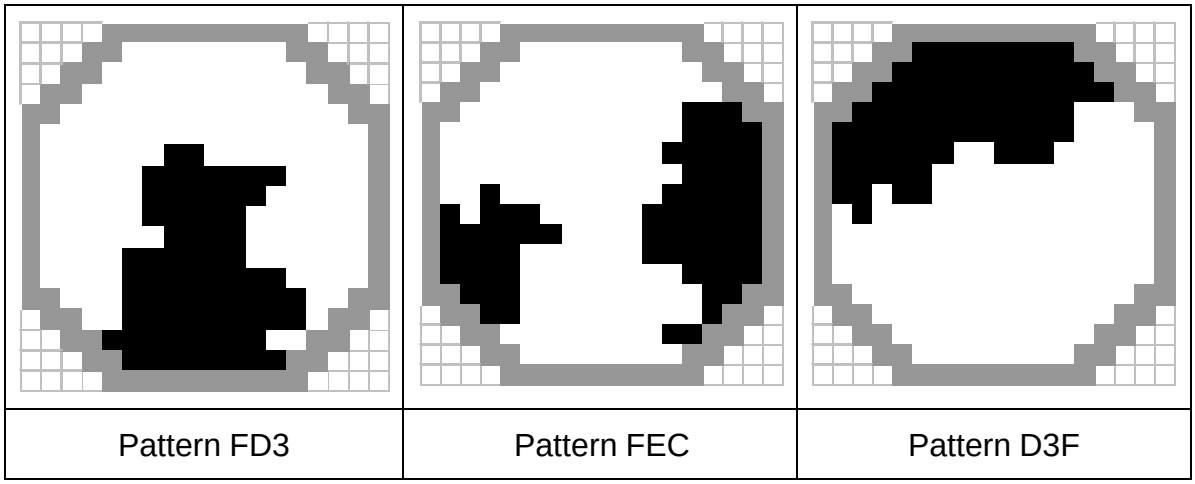

Figure 22. Patterns FD3, FEC, and D3F.

Data from these figures is summarized in Figure 23. The maximum light output from this signal remains fairly constant regardless of the particular sections of the signal that are open-circuited to the OFF state. The maximum difference of 23 candela (266 – 243) occurs at 15 volts. The maximum difference at the nominal voltage of 10.5 volts is only 12 candela (129-117). There is also a fairly constant relationship between the supply current and the maximum light intensity output of between 125 and 151 candela/amp.

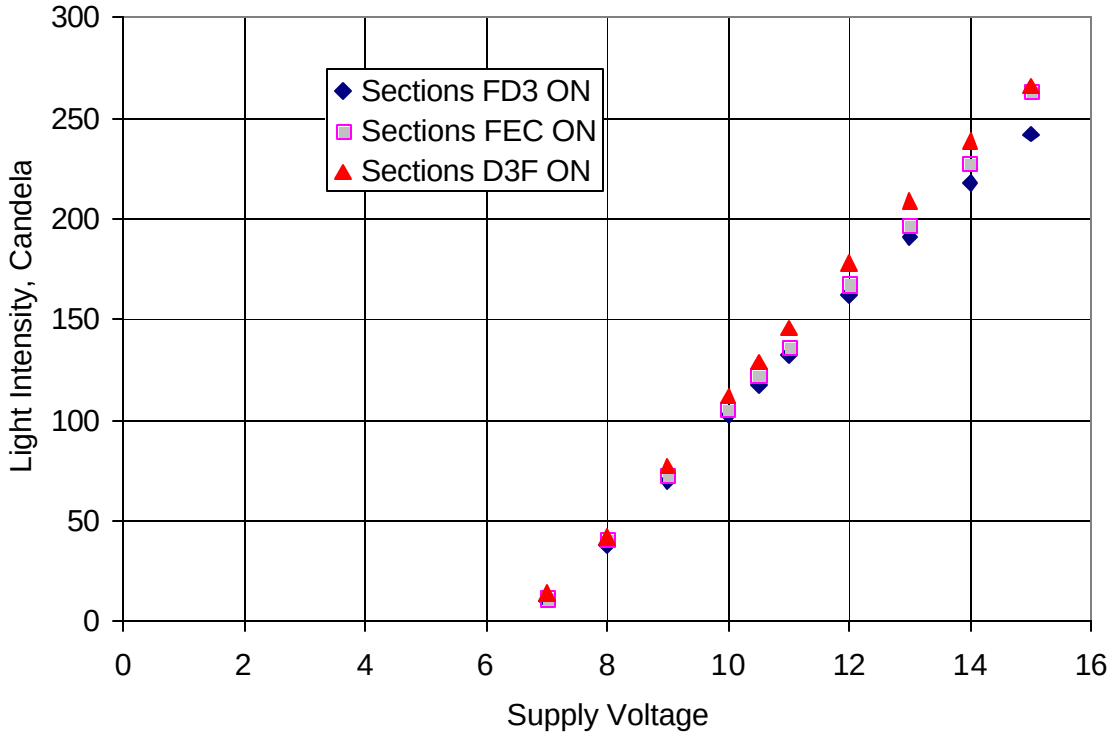

Figure 23. Maximum light intensity from NPS#1 with varying voltage input and 67% (144) LED elements ON.

Data from Safetran signal (WPS#2)

Figure 24 shows the configuration of the elements in a twelve inch signal supplied by Safetran that uses a power supply to regulate the voltage and current applied to the LEDs. This signal will be referred to as WPS#2 (“with power supply”) in this report. The WPS#2 signal uses 192 elements in 49 sets of four LEDs. Note that the LEDs are arranged in both series and parallel to minimize the effect of losing a single element. Figure 25 shows the modification to the WPS#2 signal that allows a single LED in a set of four elements to be

open-circuited. The voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

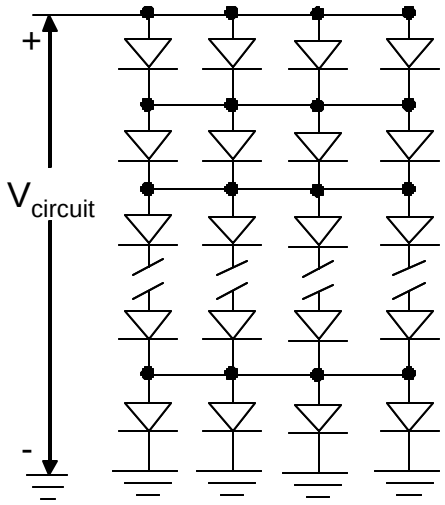

Figure 24. LED circuit configuration for WPS#2 signal

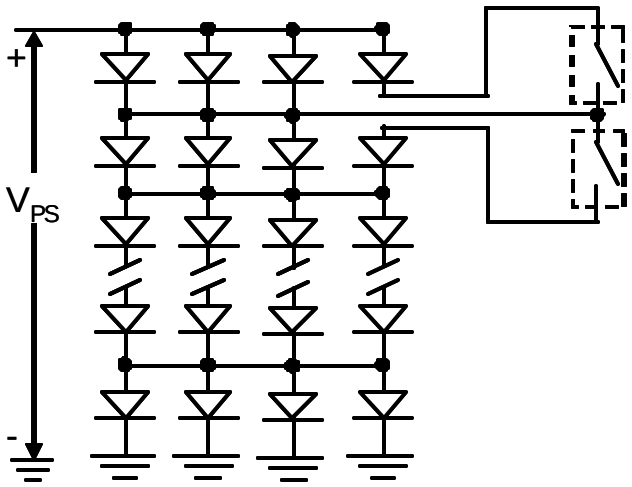

Figure 25. WPS#2 signal configured for open-circuiting

Figures A2.1.1 through A2.1.3 of the appendix show the effects of varying voltage in the range of 9.0 volts to 12.0 volts with 100% of the LED elements active. Data from these figures is summarized in Table 14. The light output from this signal is not a strong function of the supply voltage, with maximum outputs ranging from 622 candela at 10.5 volts to 614 candela at 9.0 volts. Supply currents ranged from 0.72 amps at 12.0 volts to 1.07 amps at 12 volts. Power consumption was essentially constant in the range from 8.7 to 9.6 watts. The

light-power efficiency is relatively constant, ranging from 64.0 candela/watt at 9.0 volts to 69.9 candela/watt at 12.0 volts.

Table 14. Results from WPS#2 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light - Power Efficiency (candela/watt)
9	614	1.07	9.6	64.0
10.5	622	0.86	9.1	68.4
12	608	0.72	8.7	69.9

Figure 26 shows the chromaticity results from the same tests shown in Table 14. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#2 signal.

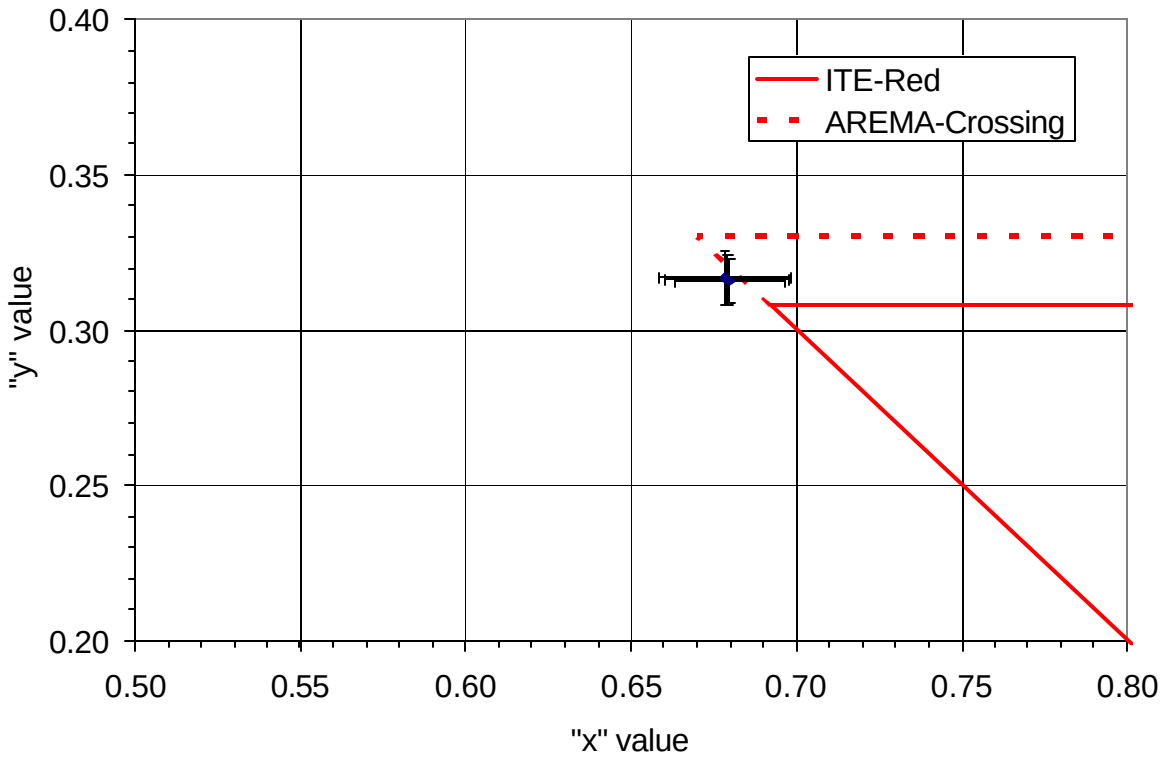

Figure 26. Chromaticity of WPS#2 with varying voltage input.

Figures A2.2.1 through A.2.2.8 of the appendix show the effects of varying the number of active LED elements from 100% to 82% via open-circuiting at a constant 10.5 volts. Table 15 summarizes these results. The light output from the WPS#2 signal is not a function of the number of active elements, with maximum outputs ranging from 564 candela at 100% (196 elements) to 548 candela at 82% (161 elements). Supply current and power consumption are essentially constant at 0.88 amps and 9.2 watts, respectively. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#2 signal. The relative insensitivity of the WPS#2 signal to the number of open-circuited elements is due to two factors:

1. the use of a power supply to regulate voltage and current, and
2. the combined series and parallel arrangement of LEDs (shown in Figure 24).

There is also a fairly constant relationship between the maximum light intensity output and the power consumption of between 58.9 and 61.9 candela/watt.

Table 15. Results from WPS#2 at 10.5 volts (open-circuits)

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
10.5	100%	196	564	0.87	9.1	61.9
10.5	97.4%	191	559	0.87	9.1	61.4
10.5	94.9%	186	554	0.87	9.1	60.9
10.5	92.3%	181	553	0.87	9.1	60.8
10.5	89.8%	176	552	0.87	9.2	60.0
10.5	87.2%	171	547	0.87	9.2	59.5
10.5	84.7%	166	545	0.88	9.2	59.2
10.5	82.1%	161	542	0.88	9.2	58.9
9.0	89.8%	176	551	1.08	9.8	56.2
10.5	89.8%	176	552	0.87	9.2	60.0
12.0	89.8%	176	548	0.87	10.5	52.2

Figure 27 shows the chromaticity results from the same tests shown in Table 15. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color

shift due to varying the percentage of ON elements via open circuiting with the WPS#2 signal.

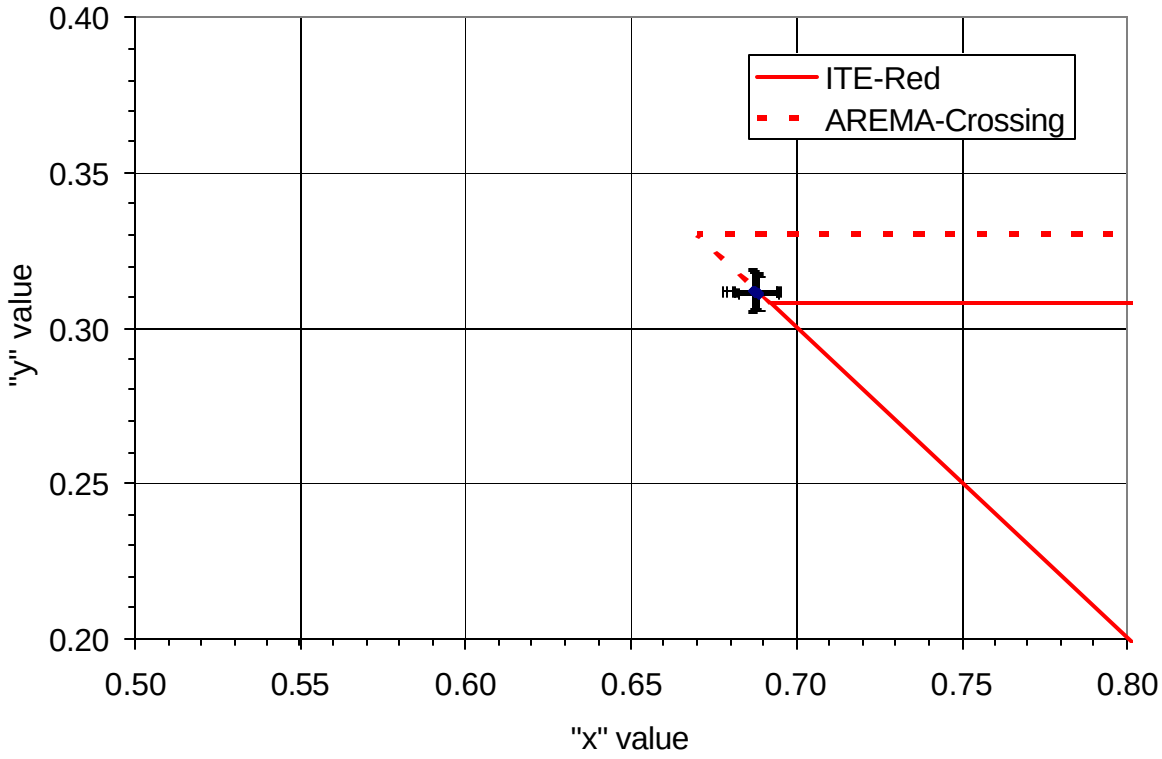

Figure 27. Chromaticity of WPS#2 at 10.5 volts (open circuits).

Figures A2.2.9 through A2.2.11 of the appendix show the effects of varying voltage in the range of 9.0 volts to 12.0 volts with 89% of the LED elements active. Data from these figures is summarized in the last three rows of Table 15. These data show again that the light output from the WPS#2 signal is not a strong function of the supply voltage, with maximum outputs ranging from 552 candela at 10.5 volts to 548 candela at 9.0 volts.

Figures A2.3.1 through A.2.3.8 of the appendix again show the effects of varying the number of active LED elements from 100% to 82% via open-circuiting at a constant 10.5 volts. Table 16 summarize these results. This is a duplicate set of data to that shown in Table 15. This second set of data was taken more than 12 months after the first set of data. As shown in Table 16, the maximum outputs have dropped to 483 candela at 100% (196 elements) to 457 candela at 85% (166 elements). Supply current and power consumption are similar to the earlier data at 0.84 amps and 9.0 watts, respectively. The fairly constant

relationship between the power consumption and the maximum light intensity output has dropped to between 50.7 and 54.9 candela/watt. There are three possible reasons for the differences in these two sets of data:

1. aging effects in the WPS#2 signal have reduced the available output,
2. the calibration of the Minolta colorimeter has shifted, and
3. small differences in the test setup have occurred.

In any event, the differences seen between these two sets of data are relatively small and are not a source of concern.

Table 16. Results from WPS#2 at 10.5 volts (open-circuits), second test

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
10.5	100.0%	196	483	0.84	8.8	54.9
10.5	97.4%	191	477	0.84	8.9	53.6
10.5	94.9%	186	473	0.84	8.9	53.1
10.5	92.3%	181	472	0.85	8.9	53.1
10.5	89.8%	176	469	0.85	8.9	52.7
10.5	87.2%	171	464	0.85	9	51.6
10.5	84.7%	166	457	0.85	9	50.7
10.5	82.1%	161	465	0.86	9	51.7
9	89.8%	176	466	1.05	9.4	49.6
10.5	89.8%	176	469	0.85	8.9	52.7
12	89.8%	176	466	0.85	10.3	45.3

Similarly, Figures A2.3.9 through A2.3.11 of the appendix show the effects of varying voltage in the range of 9.0 volts to 12.0 volts with 89% of the LED elements active. Data from these figures is summarized in the last three rows of Table 16. These data can be compared to the last three rows of Table 15.

Figure 28 shows the modification to the WPS#2 signal that allows short-circuiting of individual elements. Figures A2.4.1 through A.2.4.6 of the appendix show the effects of varying the number of active LED elements from 100% to 59.2% via short-circuiting at a constant 10.5 volts. Table 17 and Figure 29 summarize these results. The light output from the WPS#2 signal is a strong function of the number of active elements, with maximum outputs ranging from 542 candela at 100% (196 elements) to

316 candela at 59.2% (116 elements) on. Supply currents ranged from 0.85 amps at 100% to 0.49 amps at 59.2% on. Power consumption ranged from 9.0 watts at 100% to 5.1 watts at 59.2% on. These results show that the maximum light output by the WPS#2 light was proportional to the number of illuminated LEDs in the short-circuiting tests. There is also a very constant relationship between the power consumption and the maximum light intensity output of between 60.2 and 63.8 candela/watt. One interesting phenomena observed with the WPS#2 signal is that it began to blink off and on when less than 59% (116 elements) of the 196 LED elements were on.

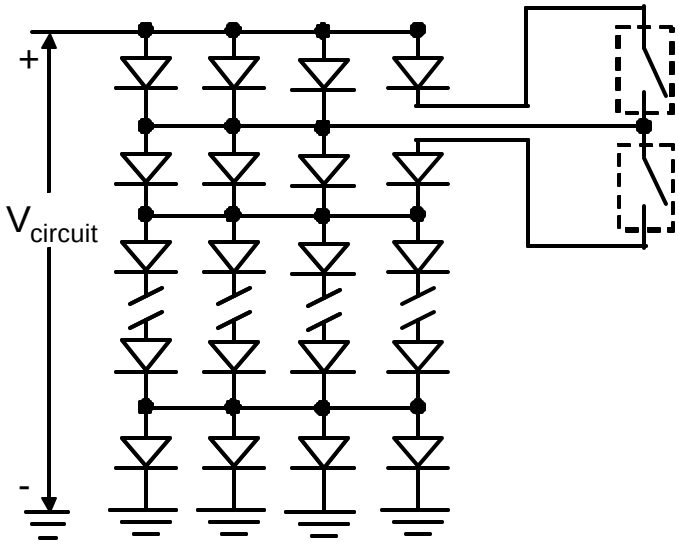

Figure 28. WPS#2 signal configured for short-circuiting

Table 17. Results from WPS#2 at 10.5 volts (short-circuits)

Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
100%	196	542	0.85	9.0	60.2
91.8%	180	507	0.78	8.2	61.8
83.7%	164	453	0.70	7.4	61.2
75.5%	148	405	0.63	6.6	61.4
67.3%	132	370	0.55	5.8	63.8
59.2%	116	316	0.49	5.1	61.9

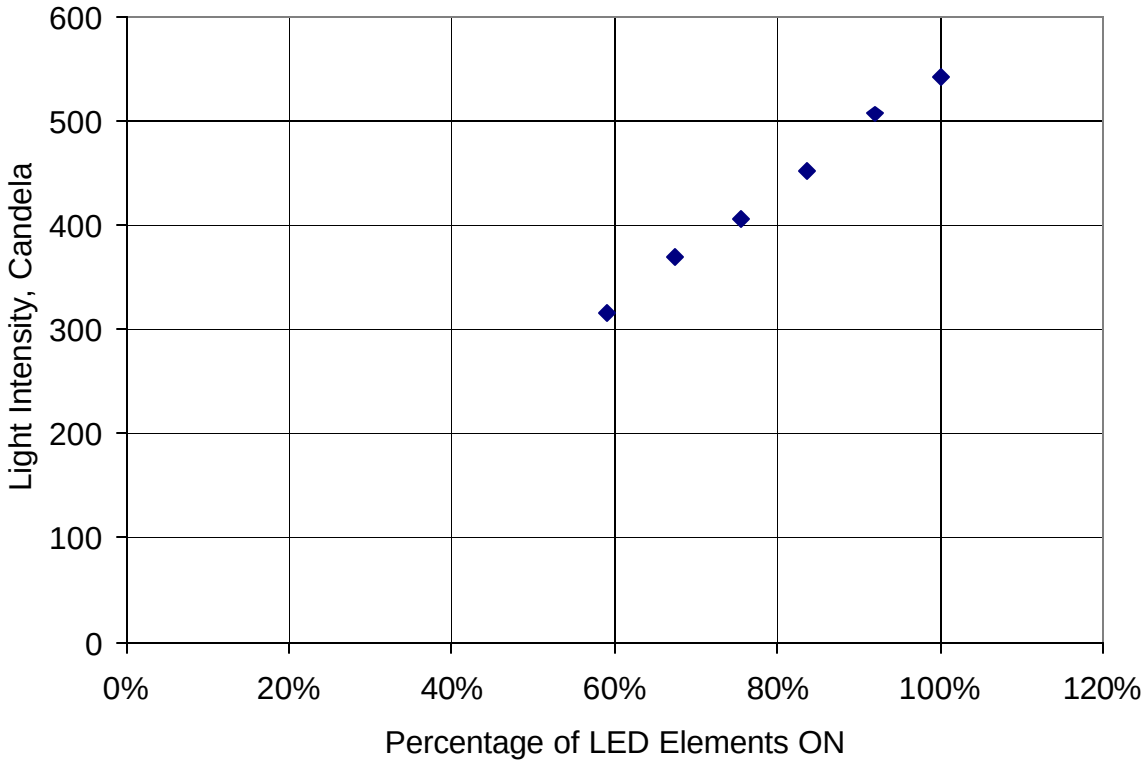

Figure 29. Maximum light intensity from WPS#2 at 10.5 volts (short-circuits)

Figure 30 shows the chromaticity results from the same tests shown in Figure 29. There is a small trend of color shift due to varying the percentage of ON elements via short circuiting with the WPS#2 signal. As the percentage of ON elements is decreased the color shifts to slightly lower “x” (red) values and slightly higher “y” (green) values. All of the results show remain clustered near the edge of the AREMA limits for red crossing signals.

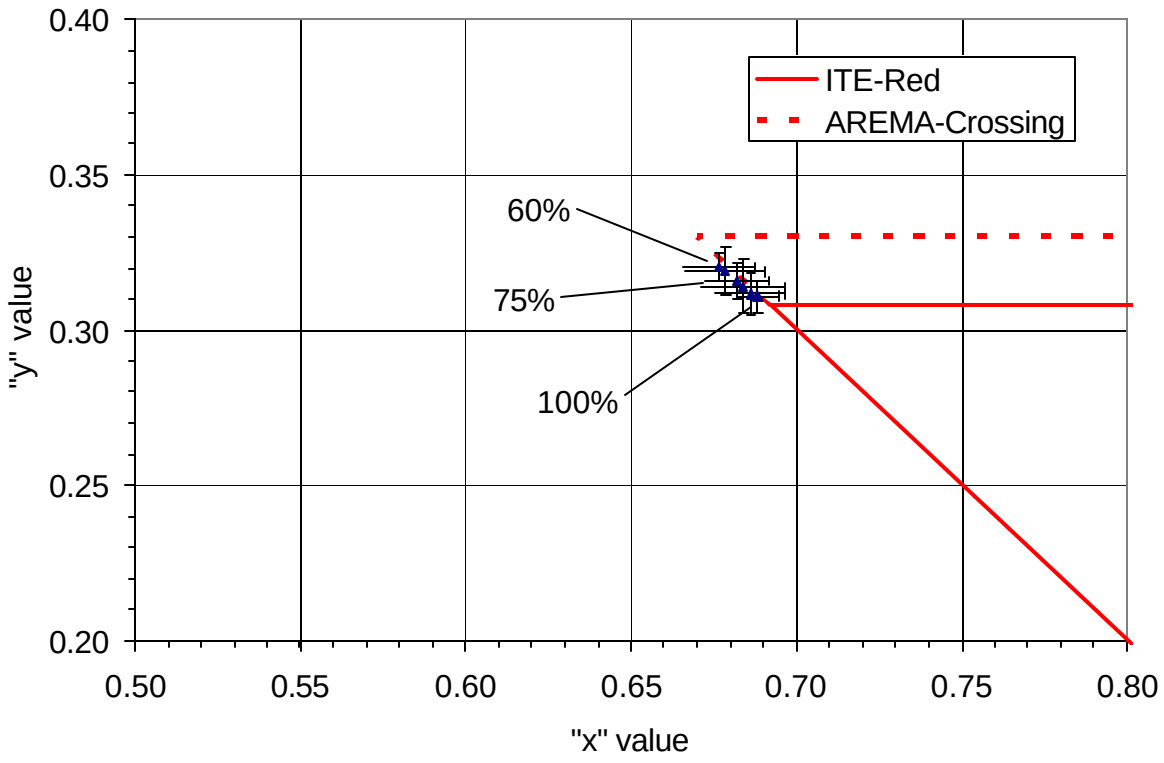

Figure 30. Chromaticity of WPS#2 at 10.5 volts (short-circuits)

Data from General Signal signal (WPS#3)

Figure 31 shows the configuration of the elements in a twelve inch signal supplied by General Signal that uses a power supply to regulate the voltage and current applied to the LEDs. This signal will be referred to as WPS#3 ("with power supply") in this report. The WPS#3 signal uses 254 visible elements in sets of three LEDs in a series circuit. Several other white LEDs are used as sidelight indicators. Due to the configuration of this signal, only open-circuit testing is possible. Figure 32 shows the modification to the WPS#3 signal that allows a set of three LED elements to be open-circuited. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

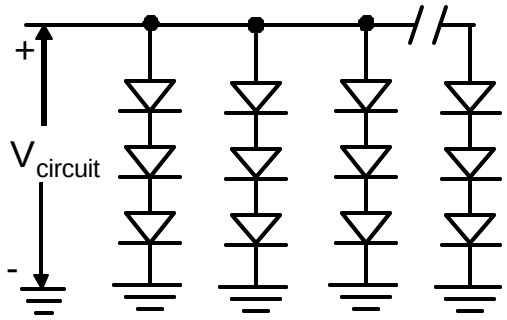

Figure 31. LED circuit configuration for WPS#3 signal

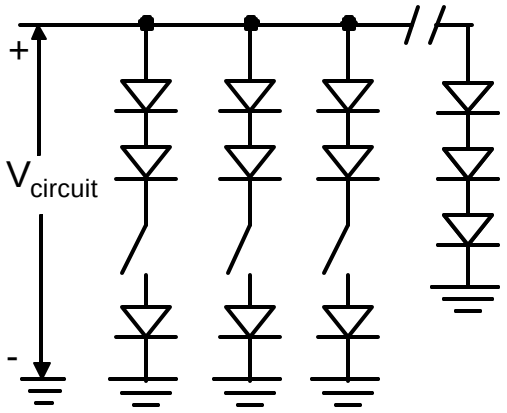

Figure 32. WPS#3 signal configured for open-circuiting

Testing of the WPS#3 signal with open-circuited elements determined that this signal has a relatively strong "heating" effect. Figure 33 shows results from a test where the signal was pointed directly at the colorimeter and not moved during 6 minutes of measurements. The data show that the light output (open triangles and diamonds) increases with time. Figure 33 also shows that the light output closely tracks the current consumption (shown by the closed triangles and diamonds). This "heating effect" was observed when all 254 of the elements were active (shown by triangles) and when 80 of the elements were open-circuited (shown by the diamonds). The amount that the light intensity changes during the test is not large -- about 35 candela out of 325 to 375 candela. However, the heating effect does make it difficult to accurately characterize the light intensity of the WPS#3 signal as a function of the number of active elements while conducting the ITE or TC position tests. Light intensity measurements taken during the ITE or TC tests with this signal are not only a function of the horizontal and vertical angle, but are also a function of time. Note that Figure 33 shows the

initial light output for 254 LEDs (~325 cd) to be less than the final light output with 164 LEDS (~332 cd).

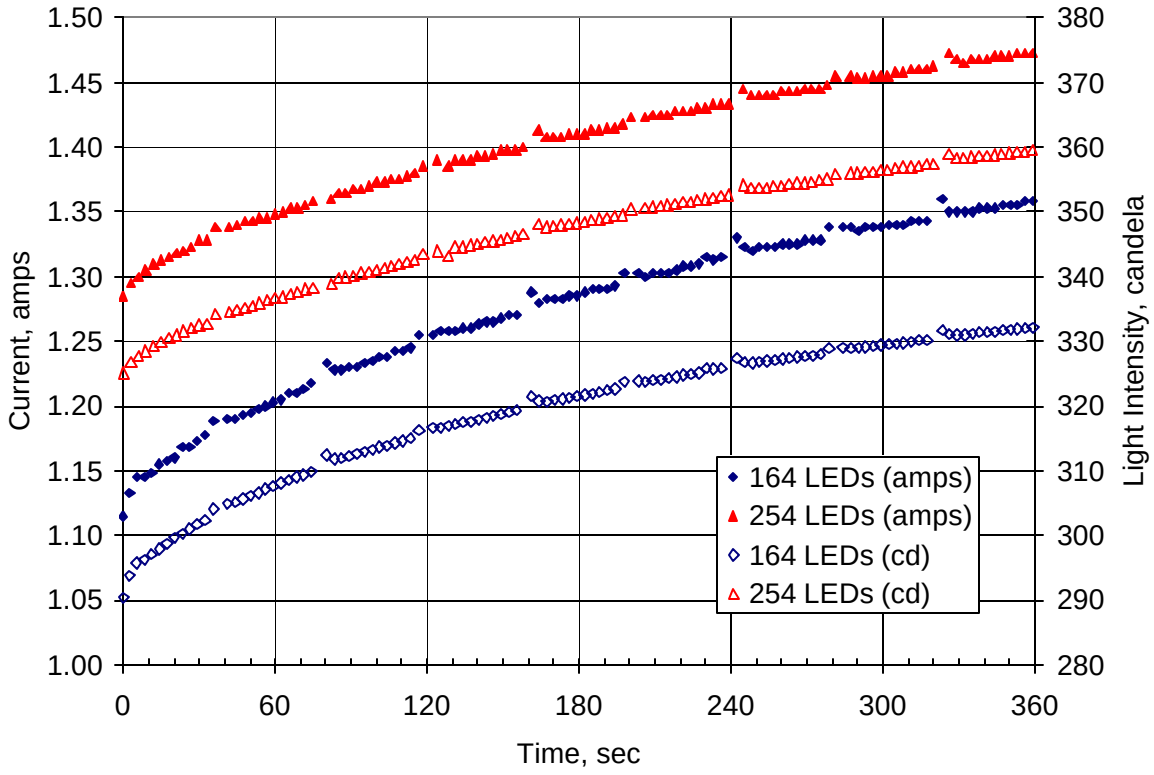

Figure 33. Current and Light Output vs. Time for WPS#3 signal.

Figures A3.1.1 through A.3.1.5 of the appendix show the effects of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures is summarized in Table 18 and Figure 34. In light of the results shown in Figure 33, these data must be interpreted carefully. The light output from this signal is a function of the voltage, with maximum outputs ranging from 391 candela at 13.5 volts to 76 candela at 7.5 volts. As shown in Table 18, supply currents ranged from 0.41 amps at 7.0 volts to 1.53 amps at 10.5 volts. Power consumption ranged from 3.1 watts at 7.5 volts to 16.2 watts at 12 volts. The maximum light outputs and the power from the nominal 10.5 volts (375 candela, 16.1 watts) up to 13.5 volts (391 candela, 16.1 watt) are essentially the same, which indicates that the power supply is effective at limiting the power once the nominal supply of 10.5 volts is applied. The light-power efficiency is also remarkably constant in the range of 23.4 to 24.6 candela/watt over the entire 7.5 to 13.5 volt range.

Table 18. Results from WPS#3 with varying voltage input.

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
7.5	100%	254	76	0.41	3.1	24.6
9.0	100%	254	273	1.26	11.3	24.1
10.5	100%	254	375	1.53	16.1	23.4
12.0	100%	254	390	1.35	16.2	24.1
13.5	100%	254	391	1.19	16.1	24.3

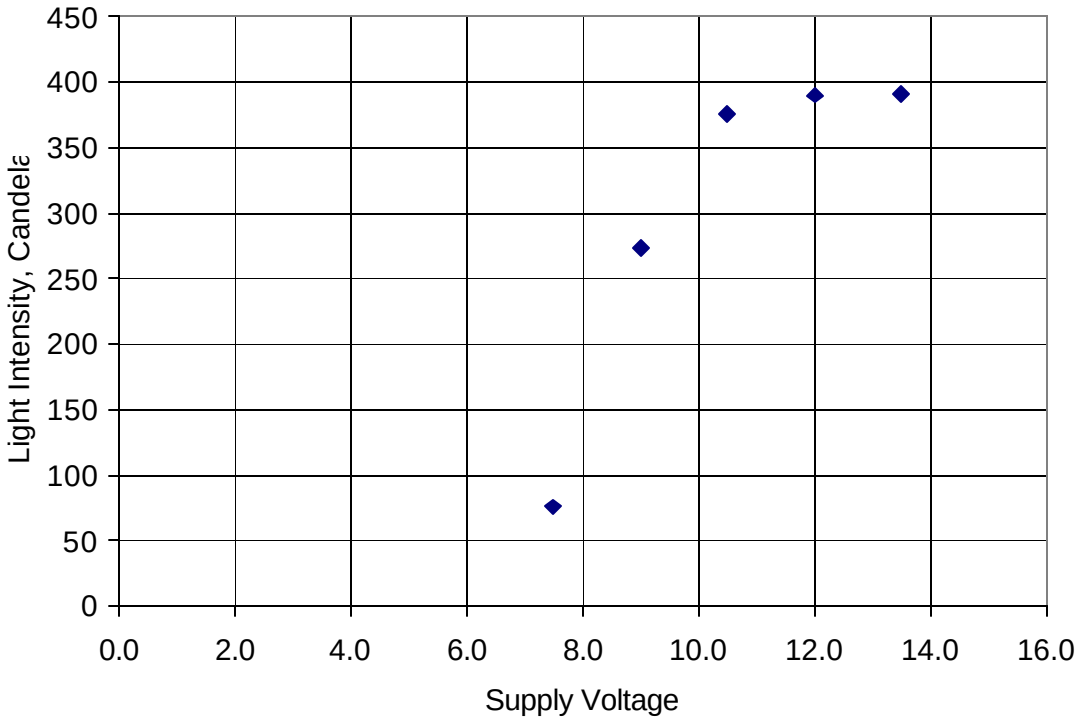

Figure 34. Maximum light intensity from WPS#3 with varying voltage input.

Figure 35 shows the chromaticity results from the same tests shown in Figure 35. Most of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The low level of light intensity (76 candela) associated with the measurements at 7.5 volts is the probable cause of the color shift of this point in Figure 35. In general, the small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. With the exception of very low voltage, there is no apparent color shift with input voltage with the WPS#3 signal.

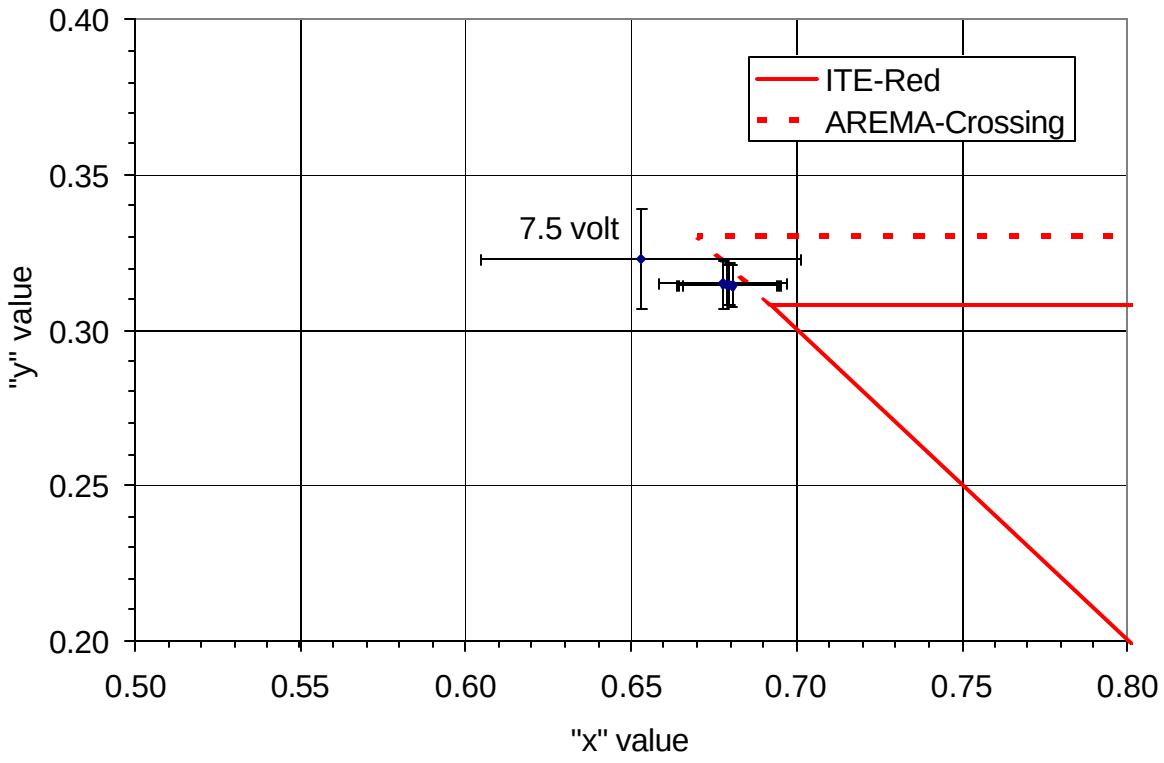

Figure 35. Chromaticity of WPS#3 with varying voltage input.

Figures A3.2.1 through A3.2.7 of the appendix show the effects of varying the number of active LED elements from 100% to 64% at a constant 10.5 volts. Table 19 summarizes these results. In light of the heating effect results shown in Figure 33, these data must be considered at least somewhat suspect, but the general trends should be correct. Note that the order of testing is the same as the order in which the figures are presented in the appendix. The light output from the WPS#3 signal is not a function of the number of active elements when there are 164 (64%) to 254 (100%) active elements. Maximum outputs range from 355 to 361 candela over this range of active elements. Supply currents were also relatively constant in the range of 1.48 to 1.58 amps. Power consumption ranged from 15.5 to 16.6 watts. These results show that the power supply is able to maintain a very constant current, power, and light intensity with up to 36% of the LED elements deactivated. There is also a very constant relationship between the power consumption and the maximum light intensity output of between 21.6 and 22.9 candela/watt.

Table 19. Results from WPS#3 at 10.5 volts.

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
10.5	100.0%	254	356	1.48	15.5	22.9
10.5	94.1%	239	355	1.5	15.8	22.6
10.5	88.2%	224	355	1.5	15.8	22.5
10.5	82.3%	209	356	1.55	16.3	21.9
10.5	76.4%	194	361	1.58	16.6	21.7
10.5	70.5%	179	359	1.58	16.6	21.6
10.5	64.6%	164	356	1.57	16.5	21.6

Figures A3.3.1 through A3.3.52 of the appendix show the effects of varying the number of active LED elements from 100% to 41% at supply voltages of 9.0, 10.0, 12.0, and 13.5 volts. Figure 36 summarizes these results. The maximum light intensity for the WP#3 signal is a function of the supply voltage up to 10 or so volts. Once the supply voltage reaches this nominal level the light output, current, and power consumption tend to remain constant. Also, the maximum light output is not a strong function of the number of active LEDs until the percentage of ON elements is somewhat less than 50%. The small increases in the light intenstity for all four voltages at the 47% level is most likely an anomaly of the testing procedure. These four data points were taken consecutively by varying the voltage with a fixed pattern of active LEDs. A small misalignment of the testing fixture can easily cause a shift of this magnitude (20 to 30 candela).

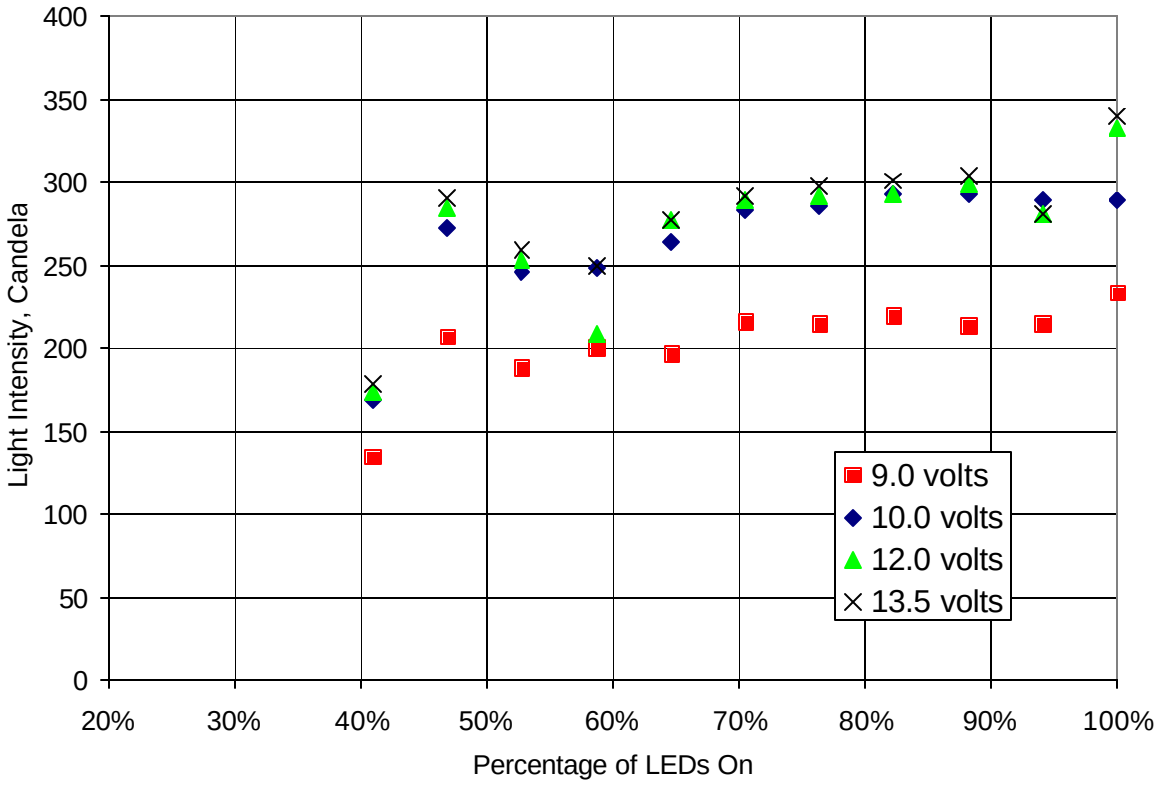

Figure 36. Maximum light intensity from WPS#3 with varying voltage and varying percentage of active LED elements.

Figure 37 shows the chromaticity results from the same tests shown in Figure 36. All of the results show similar color values clustered near the edge of the AREMA limits for red crossing signals. There is a small color shift due to varying the percentage of ON elements via open circuiting at very low levels (less than 40%) with the WPS#3 signal.

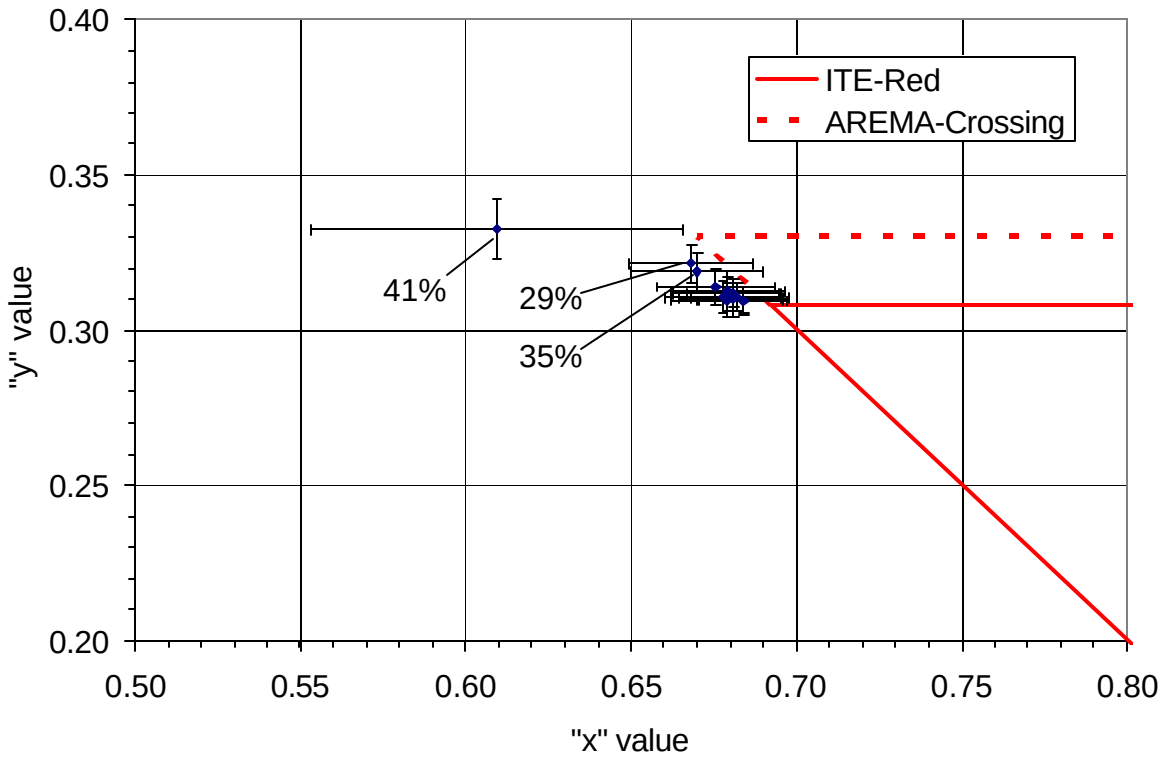

Figure 37. Chromaticity of WPS#3 at 10.5 volts (open circuit).

Data from LEDTRONICS signal (NPS#4)

The fourth twelve inch rail crossing signal tested was the LEDTRONICS unit. No power supply (NPS) is used with this signal, since the LEDs are directly connected to AC or DC power. The circuit configuration for this signal is shown in Figure 38. This signal (referred to as NPS #4 in this report) has 25 sets of five LEDs arranged in a series circuit. Four of the groups use a single diode instead of an LED, so there are a total of 121 visible elements. Due to the configuration of this signal, only open-circuit testing is possible.

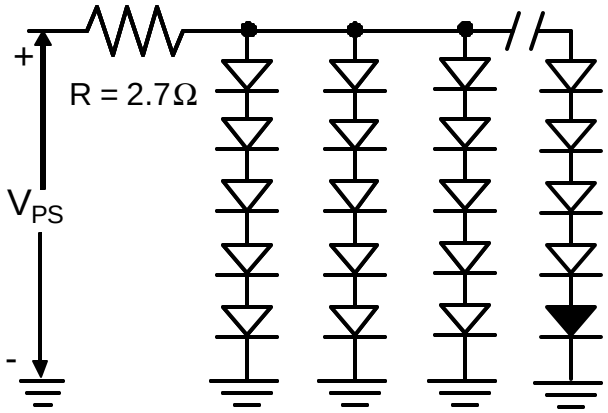

Figure 38. LED circuit configuration for NPS#4 signal.

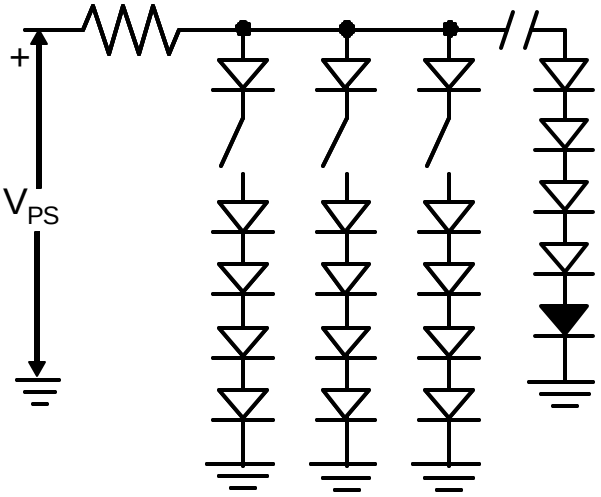

Figure 39. NPS#4 signal configured for open-circuiting.

Figures A4.1.1 through A4.1.8 of the appendix show the effects of varying voltage in the range of 9.0 volts to 15.0 volts with 100% of the LED elements active. Data from these figures is summarized in Table 20 and Figure 40. The light output from this signal is a strong function of the voltage, with maximum outputs ranging from 684 candela at 13.5 volts to 13 candela at 9.0 volts. The maximum output at the nominal 10.5 volts is approximately 173 candela. As shown in Table 20, supply currents ranged from 0.02 amps at 9.0 volts to 0.74 amps at 13.5 volts with 0.19 amps at the nominal 10.5 volt input. Power consumption ranged from 0.2 watts at 9.0 volts to 10.0 watts at 13.5 volts with 2.0 watts at the nominal 10.5 volt input. The light efficiency for the NPS#4 signal is very interesting since it remains relatively constant at a high value of about 900 candela/amp when the supply voltage is 10 volts or more.

Table 20. Results from NPS#4 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Current Efficiency (candela/amp)
9.0	13	0.02	0.2	628
10.0	105	0.12	1.2	871
10.5	173	0.19	2.0	911
11.0	252	0.28	3.1	899
12.0	420	0.45	5.4	934
13.0	592	0.65	8.5	911
13.5	684	0.74	10.0	924

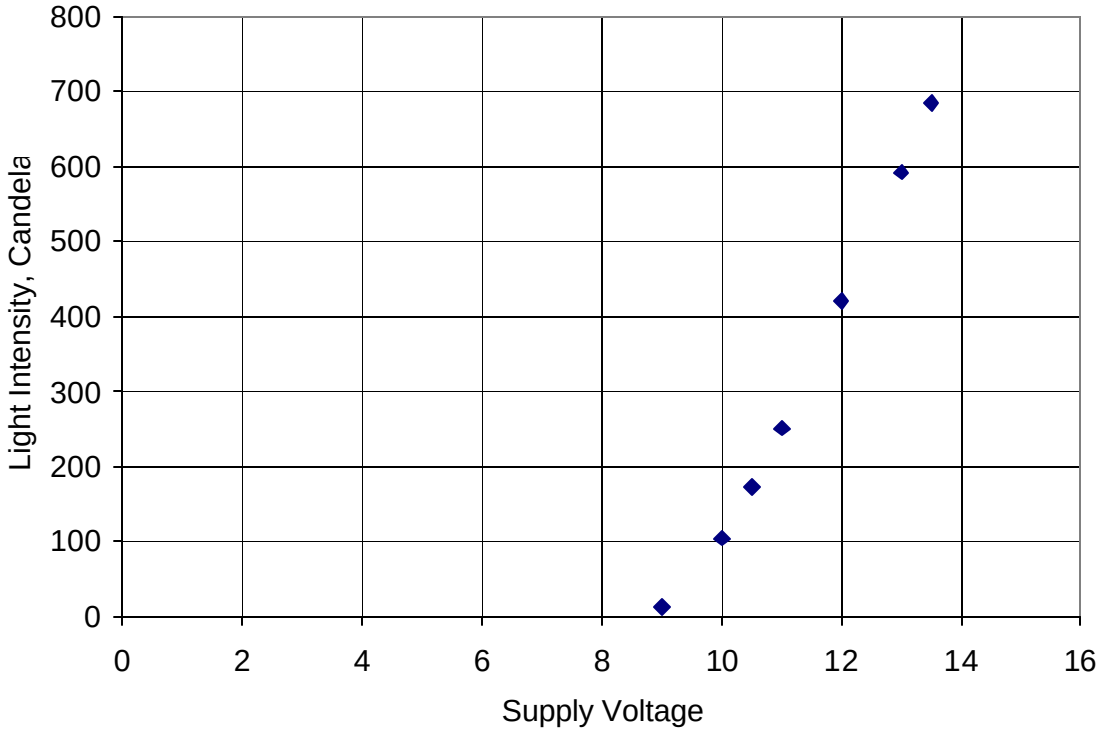

Figure 40. Maximum light intensity from NPS#4 with varying voltage input.

Figure 41 shows the chromaticity results from the same tests shown in Figure 40. With one exception, all of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The dissimilar value taken at 9.0 volts is also accompanied by a barely visible light intensity of only 13 candela. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. Except at low voltages (less than 10 volts), there is no apparent color shift with input voltage with the NPS#4 signal.

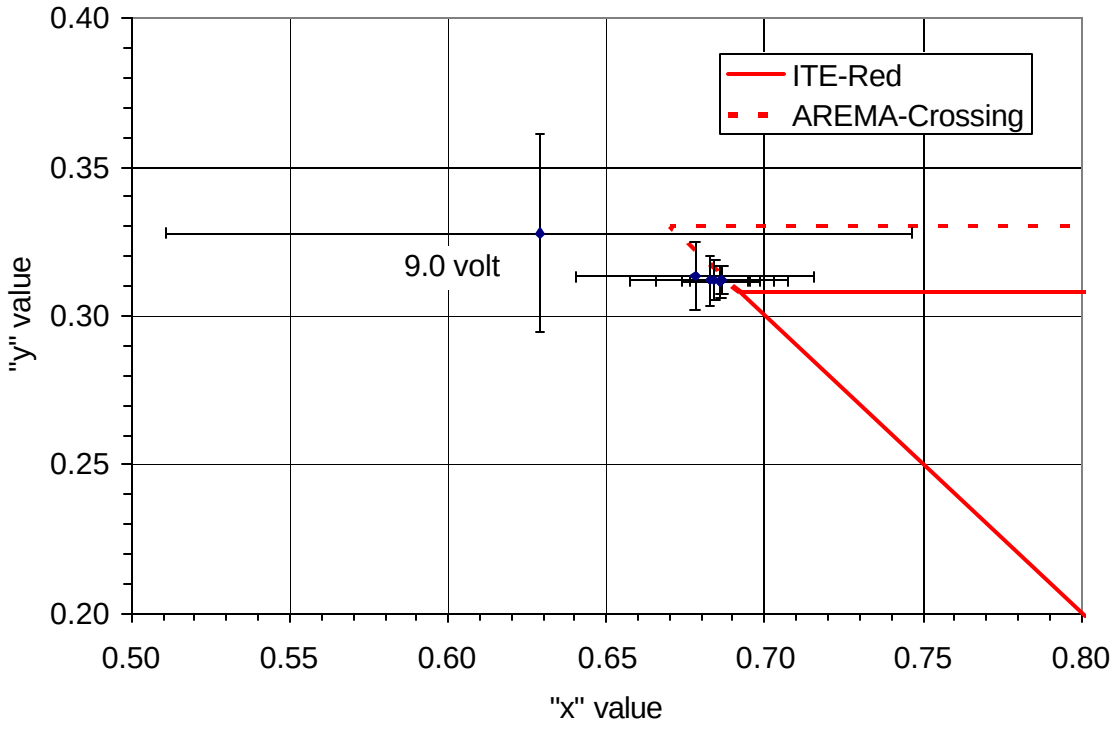

Figure 41. Chromaticity of NPS#4 with varying voltage input.

Figures A4.2.1 through A4.2.3 of the appendix show the effects of varying the number of active LED elements from 100% to 50% at a constant 12.0 volts. Table 21 summarizes these results. The light output from the NPS#4 signal is a strong function of the number of active elements, with maximum outputs ranging from 389 candela at 100% (121 elements) to 238 candela at 50% (61 elements). Supply currents ranged from 0.45 amps at 100% to 0.33 amps at 50%. Power consumption ranged from 5.4 watts at 100% to 4.0 watts at 50%. These results show a somewhat linear relationship between the number of active LED elements and the maximum light intensity output.

Table 21. Results from NPS#4 at 12.0 volts.

Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light Efficiency (candela/amp)
100%	121	389	0.45	5.4	864
75%	91	328	0.40	4.8	819
50%	61	238	0.33	4.0	722

Figure 42 shows the chromaticity results from the same tests shown in Table 21. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There appears to be a small color shift due to varying the percentage of ON elements via open circuiting with the NPS#4 signal, but all of the variations were well with the limits for the AREMA red crossing signal.

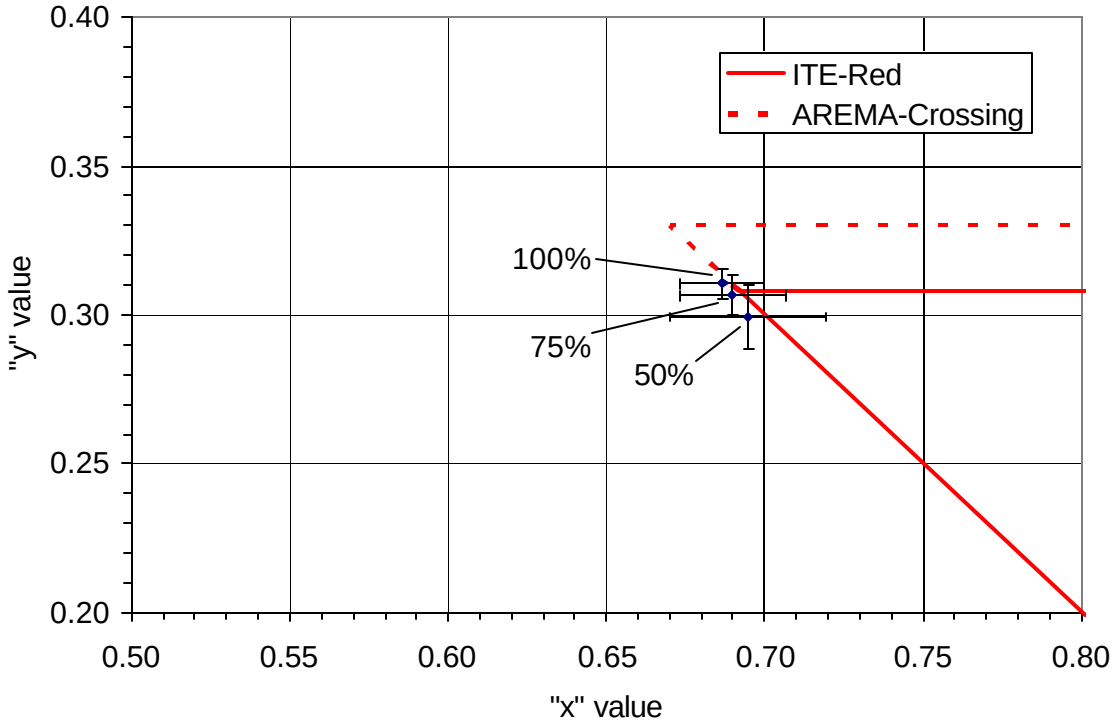

Figure 42. Chromaticity of NPS#4 with varying percentages of active LEDs.

Figure 43 summarizes maximum light intensities for the WPS#4 signal as a function of power supply voltage and percentage of active LED elements. This figure shows an essentially linear relationship between the maximum light intensity and power supply voltage above 10 volts. Figures 44 and 45 show the power supply current and the power consumption for the same data shown in Figure 43.

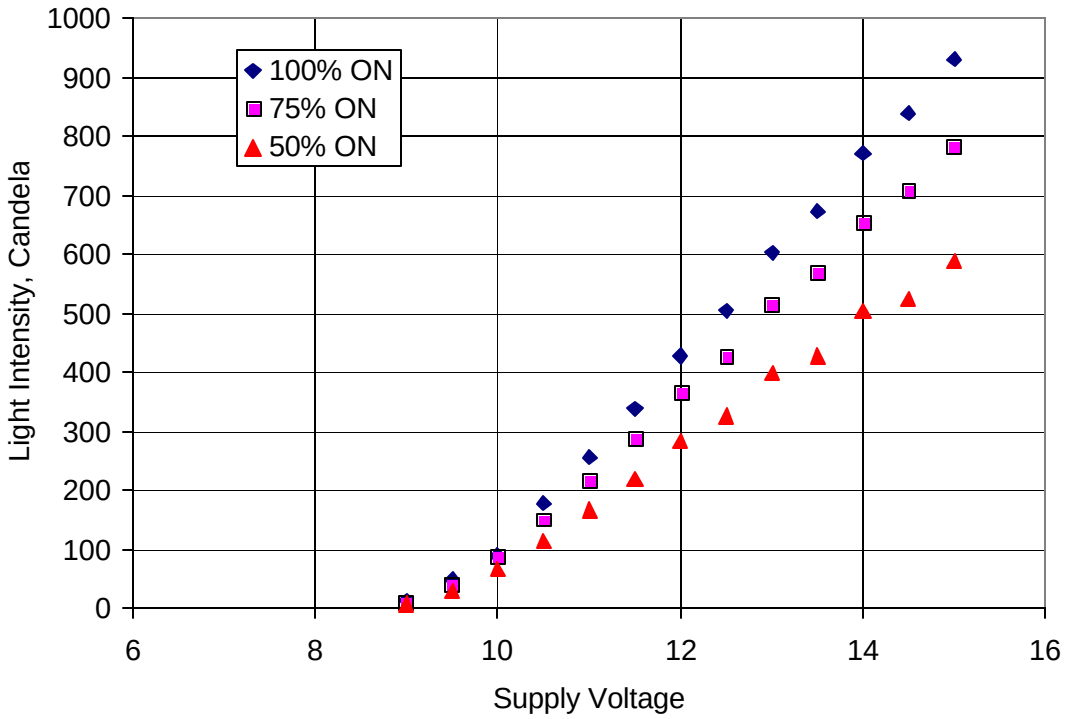

Figure 43. Maximum light intensity from NPS#4 at varying voltages and varying percentages of active LEDs.

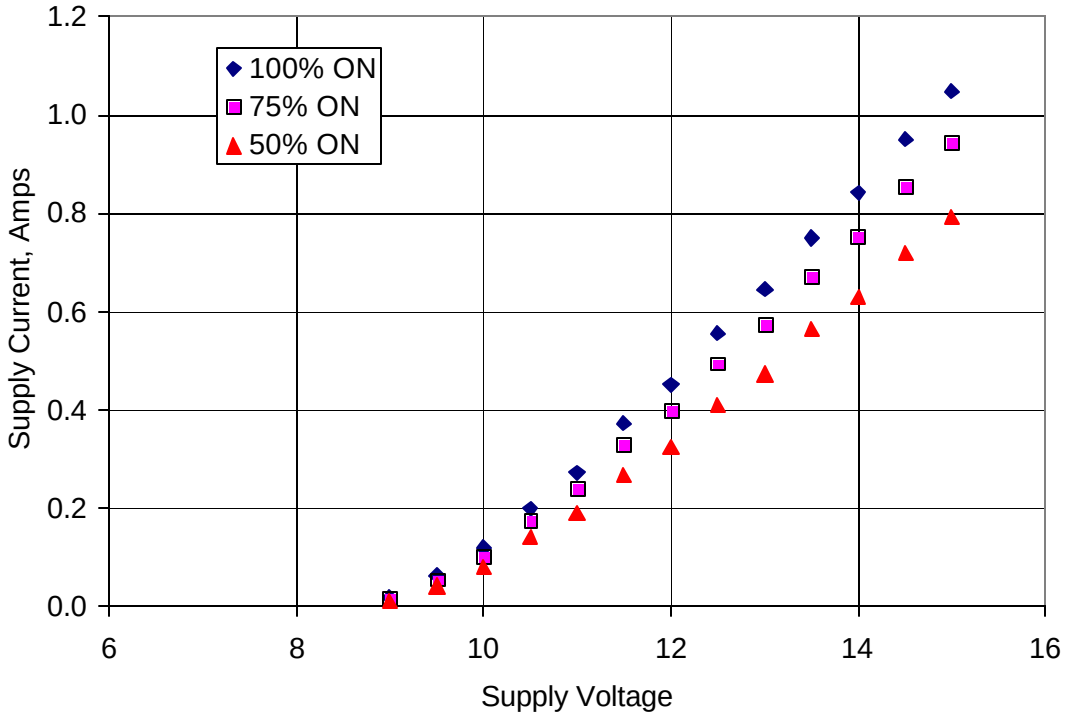

Figure 44. Power supply current for NPS#4 at varying voltages and varying percentages of active LEDs.

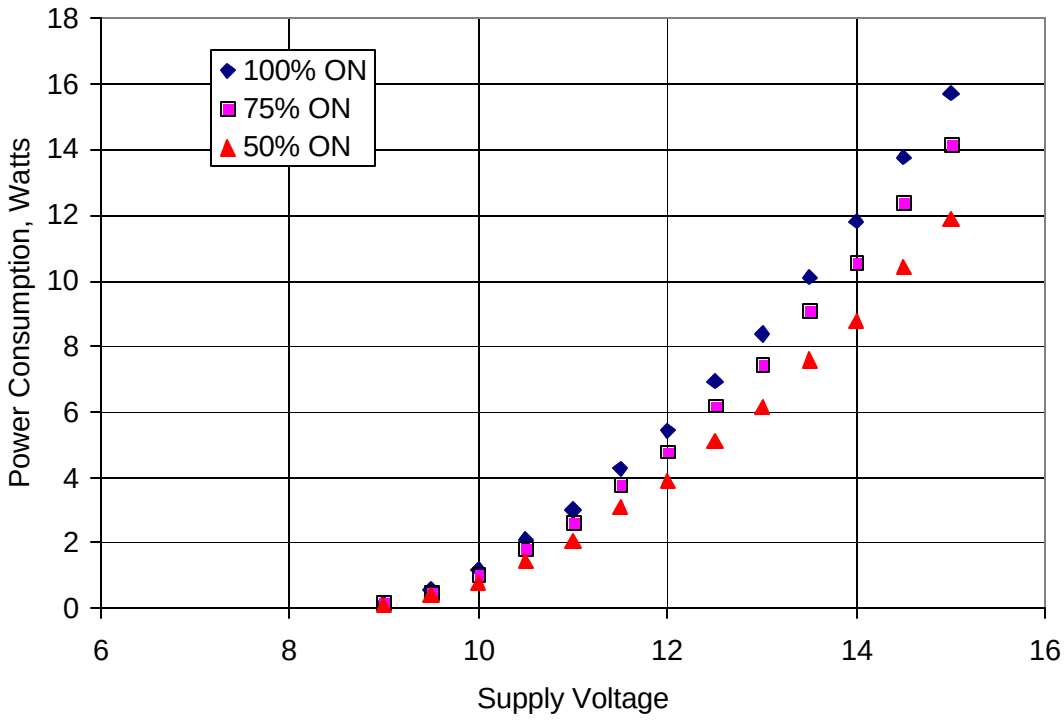

Figure 45. Power consumption for NPS#4 at varying voltages and varying percentages of active LEDs.

Data from Electrotech signal (WPS#5)

Figure 46 shows the configuration of the elements in a twelve inch signal purchased from Electrotech that uses a power supply to regulate the voltage and current applied to the LEDs. This signal (referred to as WPS#5 in this report) has 42 sets of ten LEDs arranged in a series circuit, for a total of 420 visible elements. Due to the configuration of this signal, only open-circuit testing is possible. Figure 47 shows the modification to the WPS#5 signal that allows a set of ten LED elements to be open-circuited. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

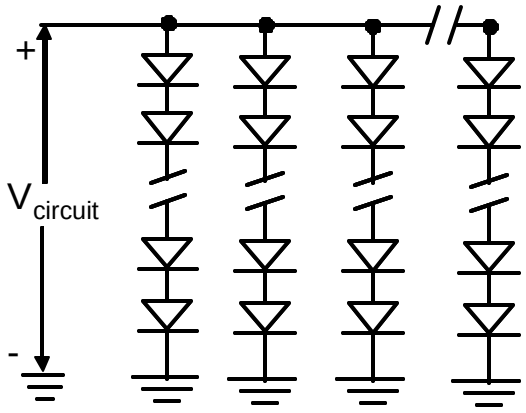

Figure 46. LED circuit configuration for WPS#5 signal

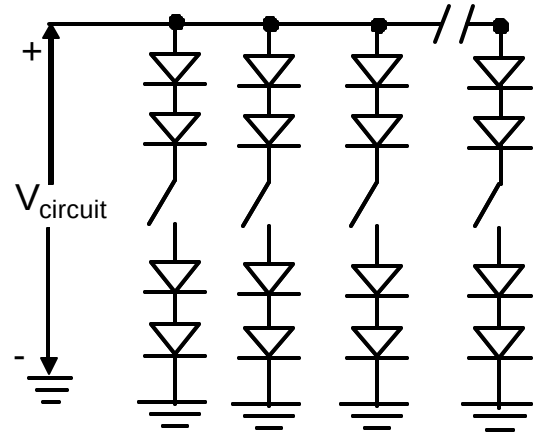

Figure 47. WPS#5 signal configured for open-circuiting

Figures A5.1 through A5.6 of the appendix show the effects of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures are summarized in Table 22. The maximum light output for the WPS#5 signal is not a function of the supply voltage. Maximum outputs range from 180 candela at 9.0 volts to 165 candela at 13.5 volts. As shown in Table 22, supply currents ranged from 1.91 amps at 7.5 volts to 0.84 amps at 13.5 volts. Power consumption ranged from 14.3 watts at 7.5 volts to 11.3 watts at 13.5 volts. The maximum light outputs and the power from the nominal 10.5 volts (168 candela, 12.1 watts) up to 13.5 volts (165 candela, 11.3 watt) are essentially the same, which indicates that the power supply is effective at limiting the power once the nominal supply of 10.5 volts is applied. The light-power efficiency is also relatively constant in the range of 12.3 to 14.6 candela/watt.

Table 22. Results from WPS#5 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
7.5	176	1.91	14.3	12.3
9.0	180	1.44	13.0	13.9
10.0	169	1.23	12.3	13.7
10.5	168	1.15	12.1	13.9
12.0	166	0.97	11.6	14.3
13.5	165	0.84	11.3	14.6

Figure 48 shows the chromaticity results from the same tests shown in Table 22. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#5 signal.

The signal was modified according to the schematic shown in Figure 47. Unfortunately, the WPS#5 signal did not work correctly after the open-circuit modifications. As shown in Figure 49 the 420 LED elements are very closely spaced in this signal. Some type of inadvertent modification -- most likely cutting the wrong circuit board trace -- caused the modified signal to not work properly. Since the WPS#5 signal had such a low intensity output (160 candela) even with all 420 elements operating, there was no justification for continuing the investigation of this signal with non-illuminated elements.

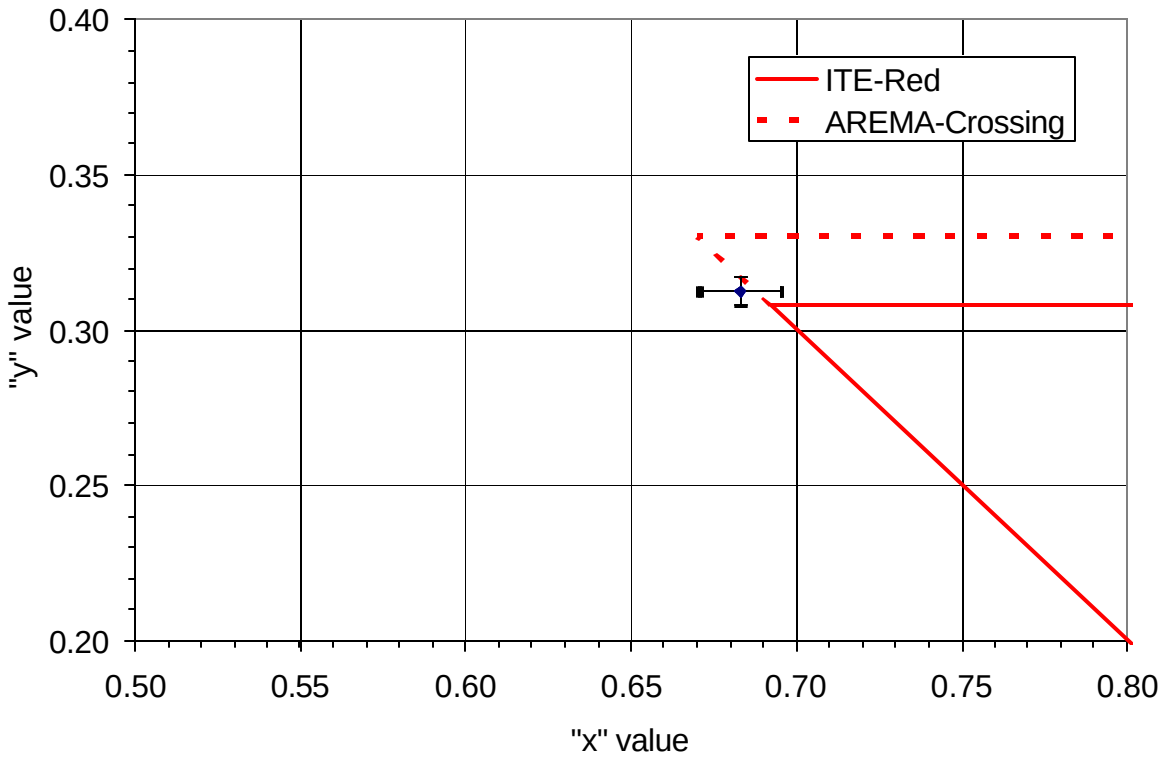

Figure 48. Chromaticity of the WPS#5 signal at varying voltages.

Figure 49. Interior of the WPS#5 signal.

Data from Dialight signal (WPS#6)

Figure 50 shows the configuration of the elements in a twelve inch signal supplied by Dialight that uses a power supply to regulate the voltage and current applied to the LEDs. This signal (referred to as WPS#6 in this report) has only 18 high-intensity LED elements. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

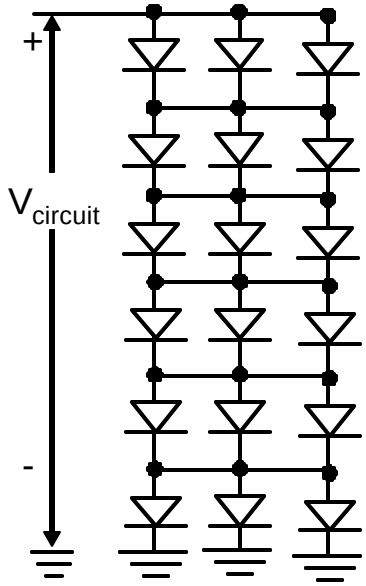

Figure 50. LED circuit configuration for WPS#6 signal

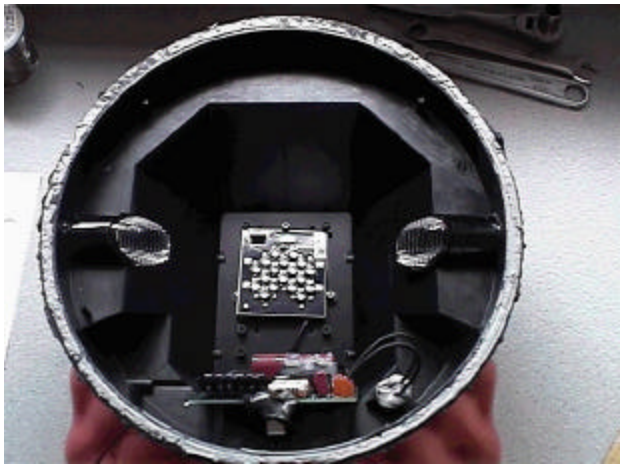

Figure 51. Interior of the WPS#6 signal.

Figures A6.1.1 through A6.1.6 of the appendix show the effects of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures are summarized in Table 23. The maximum light output for the WPS#6 signal is not a function of the supply voltage. Maximum outputs range from 393 candela at 10.0 volts to 279 candela at 7.5 volts. As shown in Table 23, supply currents ranged from 2.05 amps at 9.0 volts to 1.11 amps at 13.5 volts. Power consumption ranged from 13.7 watts at 7.5 volts to 15.0 watts at 13.5 volts. The maximum light outputs and the power from 10.5 volts and up are essentially the same, which indicates that the power supply is effective at limiting the power once the nominal supply of 10.5 volts is applied. The light-power efficiency remained relatively constant at 22.6 to 25.3 candela/watt in this range as well.

Table 23. Results from WPS#6 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light - Power Efficiency (candela/watt)
7.5	279	1.82	13.7	20.4
9.0	368	2.05	18.5	19.9
10.0	393	1.74	17.4	22.6
10.5	390	1.59	16.7	23.4
12.0	385	1.30	15.6	24.7
13.5	379	1.11	15.0	25.3

Figures A6.2.1 through A6.5.6 of the appendix show the results of four additional sets of tests of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures are summarized in Figure 52. These results also show the typical variation between tests of identical signals. Variations on the order of ±50 candela for any given test point are not uncommon.

Figure 53 shows the chromaticity results from the same tests shown in Figure 52. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#6 signal.

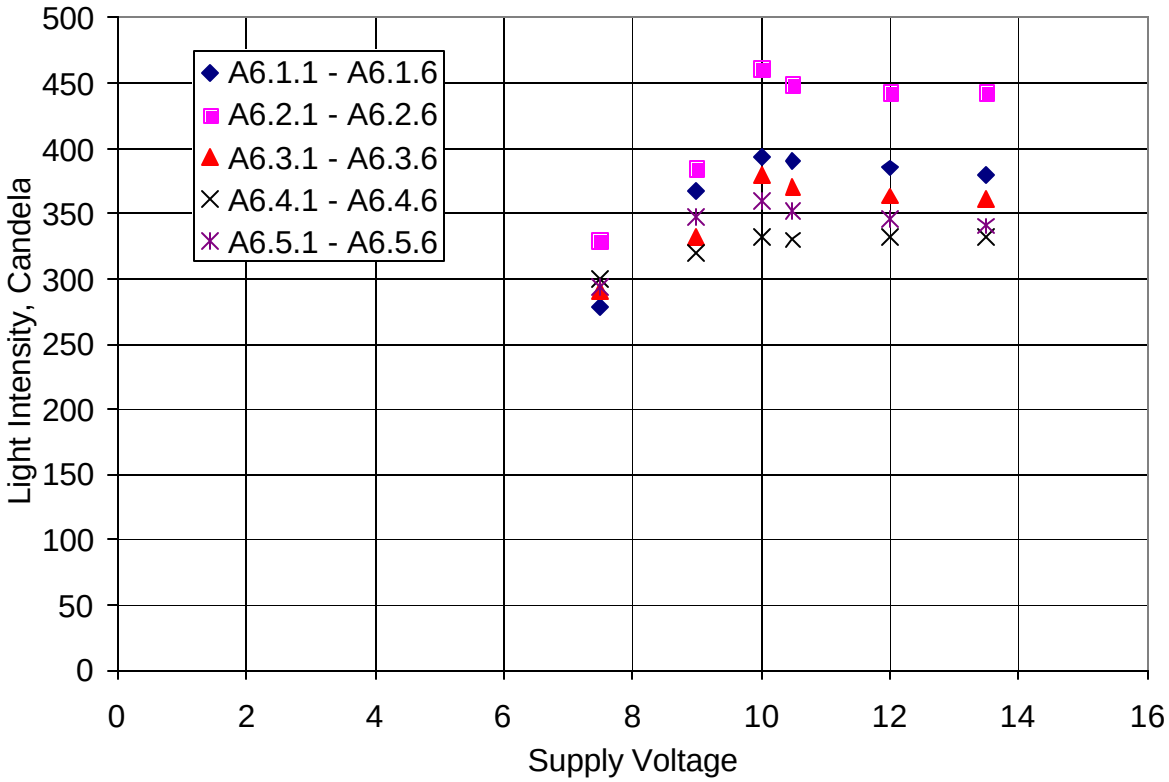

Figure 52. Maximum light intensity from WPS#6 with varying voltage input.

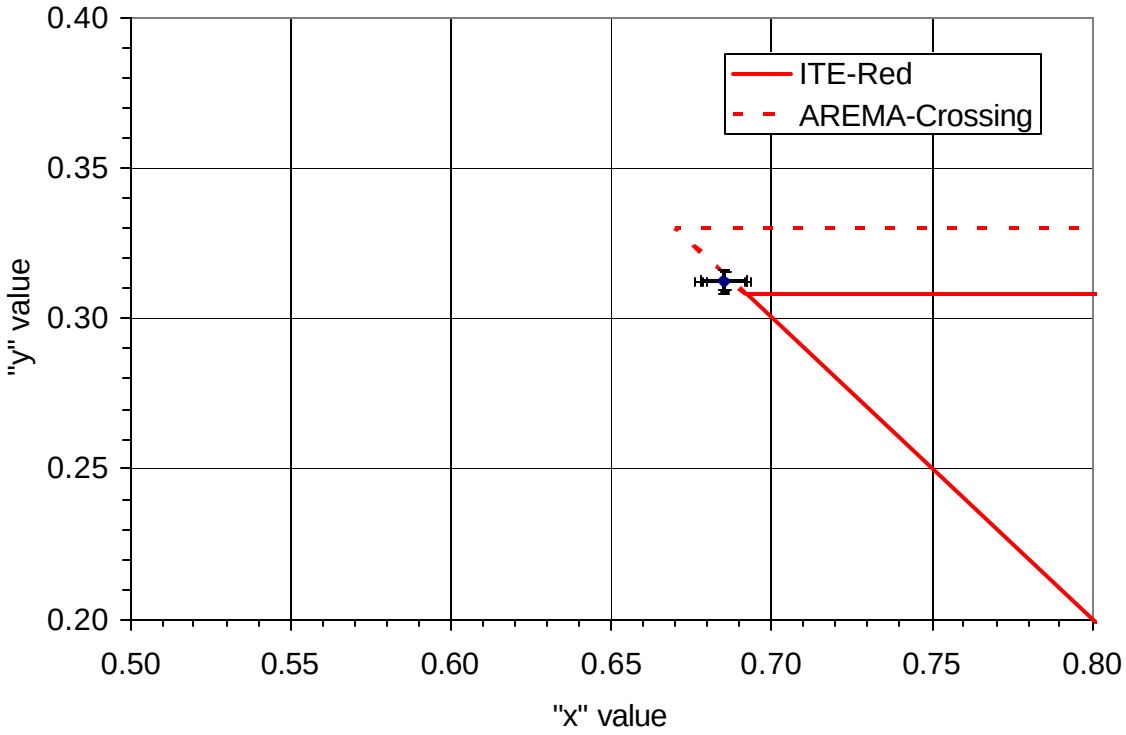

Figure 53. Chromaticity of the WPS#6 signal with varying voltage.

Modification of this signal to deactivate individual LED elements was difficult and ultimately not successful. The high-intensity LED "chips" use surface mount technology which is less amenable to modification since the entire circuit appears on only one side of the circuit board. This particular signal uses a pre-packaged circuit board which contains the 18 high-intensity LED chips. Two additional circuit boards were purchased from LumiLeds and were modified as shown in Figure 54. Unfortunately, the WPS#6 signal did not work correctly after the open-circuit modifications. A component on the power supply for the circuit board (most likely a capacitor) failed and rendered the entire unit inoperable. Due to the very small number of LED elements (18), successful testing with non-operable elements would have been difficult at best. No further testing with the WPS#6 signal was conducted.

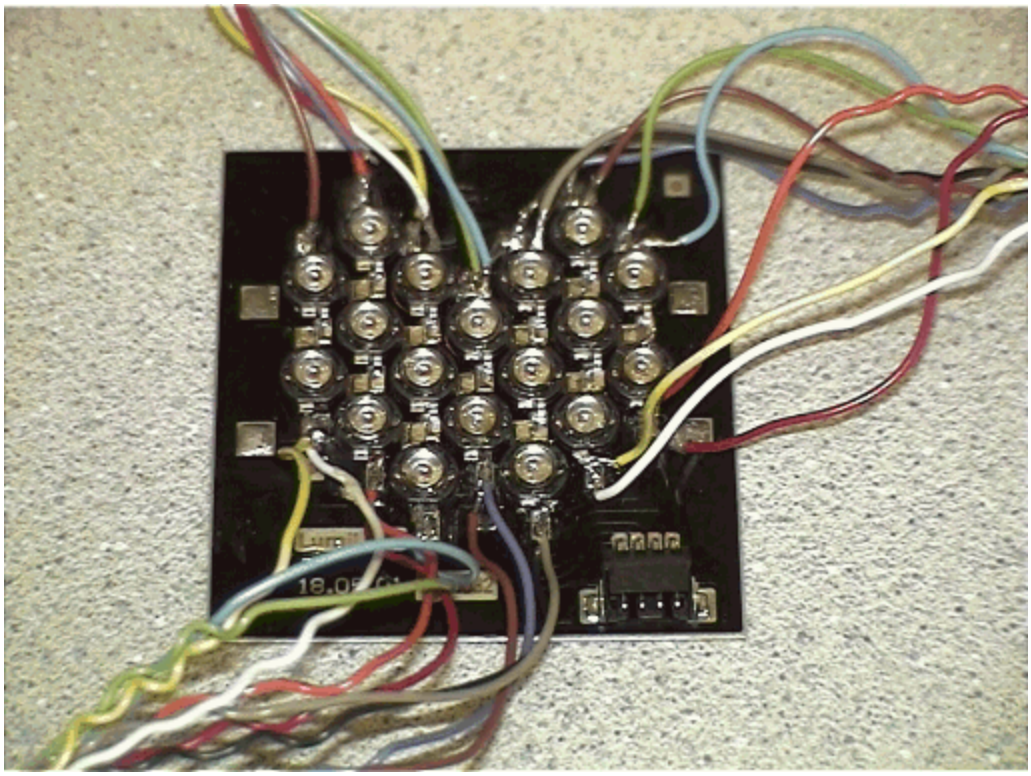

Figure 54. Modification to WPS#6 signal circuit board.

Data from Gelcore signal (WPS#7)

Figure 55 shows the configuration of the elements in a eight inch, red, wayside signal (#RM4 RC 75) supplied by Gelcore. This signal (referred to as WPS#7 in this report) has 88 LED elements arranged in 22 groups of 4 in a series/parallel circuit as shown in Figure 55. The WPS#7 signal uses a power supply to regulate the voltage and current applied to the LEDs. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

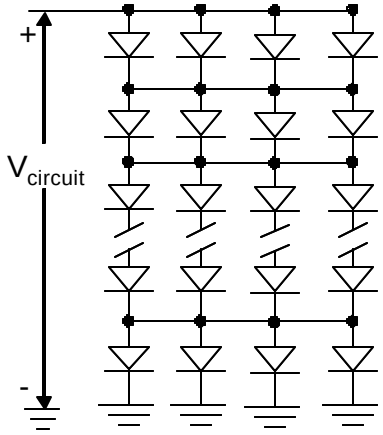

Figure 55. LED circuit configuration for WPS#7 signal

This eight inch wayside signal was equipped with a lens that gives a narrower (13 degree) field of view than the twelve inch crossing signals. The six twelve inch signals tested earlier (NPS#1, WPS#7, WPS#3, NPS#4, WPS#5, WPS#6) all used the same point source correction factor to convert the candela measurement made at 57 feet. An eight inch signal would ideally be measured at a distance of 38.2 feet as shown in Figure 56.

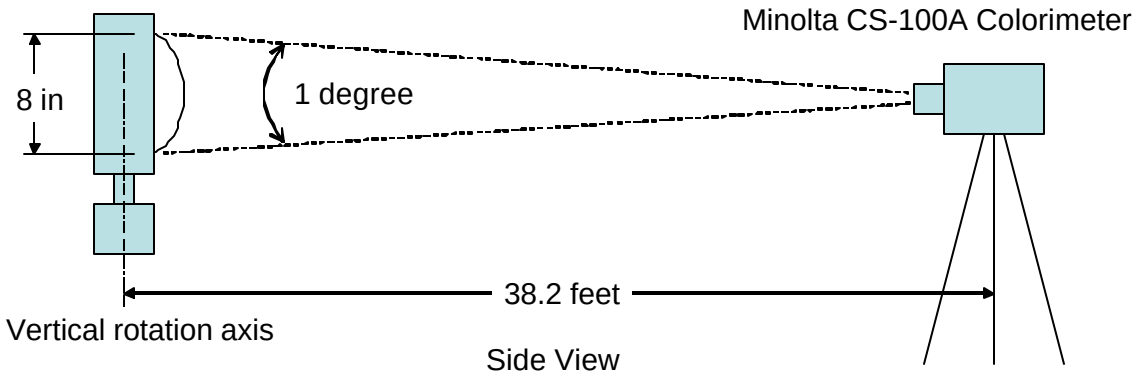

Figure 56. Camera setting distance for 8 inch signals.

Figures A7.1.1 through A7.3.8 show the results of a series of tests that were conducted to determine the point source correction factor for the red signal. Figure 57 summarizes the results from this series of tests, which were very inconsistent. Under ideal circumstances the output of this signal should have somewhat approximated the inverse square law shown in Figure 57. In several cases moving the signal further from the measuring colorimeter caused the maximum light intensity to increase – which should not have happened. The exact reason for the erratic behavior of this signal is unknown, but is most likely due to the narrow beam angle (13 degrees) of the WPS#7 signal making the initial alignment more critical than with the twelve inch crossing signals. Due to the erratic measurements of the WPS#7 signal at different distances, the point source correction was not applied to any of the readings for the eight inch signals (WPS#7, WPS#8, and WPS#9).

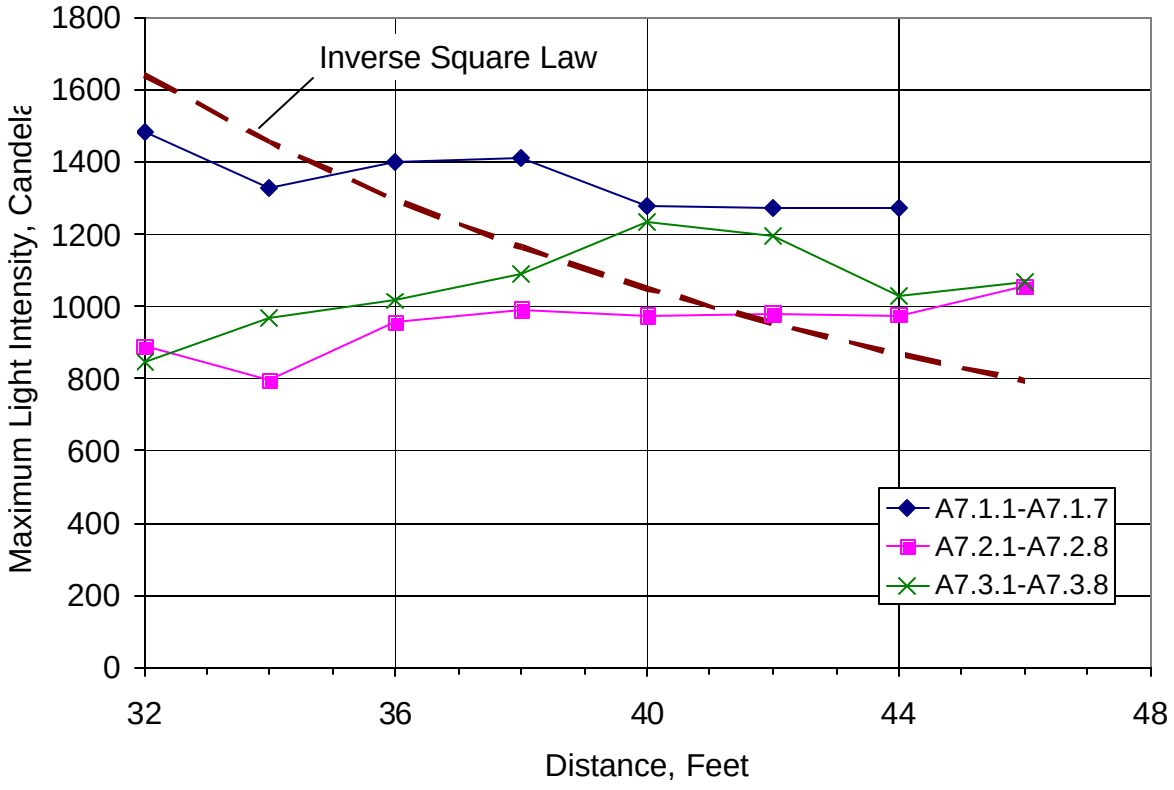

Figure 57. Maximum light intensity vs. distance for WPS#7

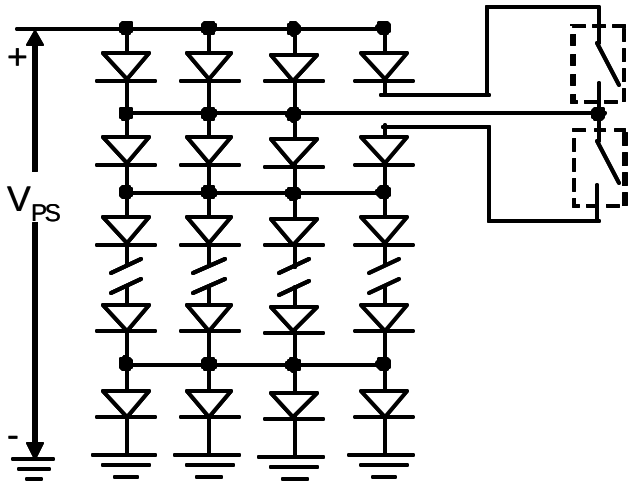

Figure 58. WPS#7 signal configured for open-circuiting

Figures A7.6.1 through A.7.6.16 of the appendix show the effects of varying the number of active LED elements from 95% (84 active elements) to 77% (68 active elements) via open-circuiting at a constant 10.0 volts. Table 24 and Figure 59 summarize these results. The light output from the WPS#7 signal is not a function of the number of active elements, with maximum outputs ranging from 1163 to 1205 candela. Supply current and power consumption are essentially constant at 1.46-1.50 amps and 14.6-15.0 watts, respectively. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#7 signal. The relative insensitivity of the WPS#7 signal to the number of open-circuited elements is due to two factors:

3. the use of a power supply to regulate voltage and current, and
4. the combined series and parallel arrangement of LEDs (shown in Figure 55).

There is also a constant relationship between the maximum light intensity output and the power consumption of between 79.2 and 81.5 candela/watt.

Table 24. Results from WPS#7 at 10.0 volts (open-circuits)

Figure	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
A7.6.1	95.5%	84	1170	1.46	14.6	80.1
A7.6.2	95.5%	84	1165	1.46	14.6	79.7
A7.6.3	95.5%	84	1177	1.46	14.6	80.5
A7.6.4	95.5%	84	1191	1.46	14.6	81.5
A7.6.5	95.5%	84	1163	1.46	14.6	79.6
A7.6.6	95.5%	84	1186	1.46	14.6	81.1
A7.6.7	90.9%	80	1169	1.47	14.7	79.4
A7.6.8	90.9%	80	1194	1.47	14.7	81.2
A7.6.9	90.9%	80	1165	1.47	14.7	79.2
A7.6.10	90.9%	80	1175	1.47	14.7	79.9
A7.6.11	86.4%	76	1200	1.48	14.8	81.0
A7.6.12	86.4%	76	1198	1.48	14.8	80.9
A7.6.13	86.4%	76	1205	1.48	14.8	81.3
A7.6.14	81.8%	72	1211	1.49	14.9	81.2
A7.6.15	81.8%	72	1190	1.49	14.9	79.8
A7.6.16	77.3%	68	1190	1.5	15.0	79.2

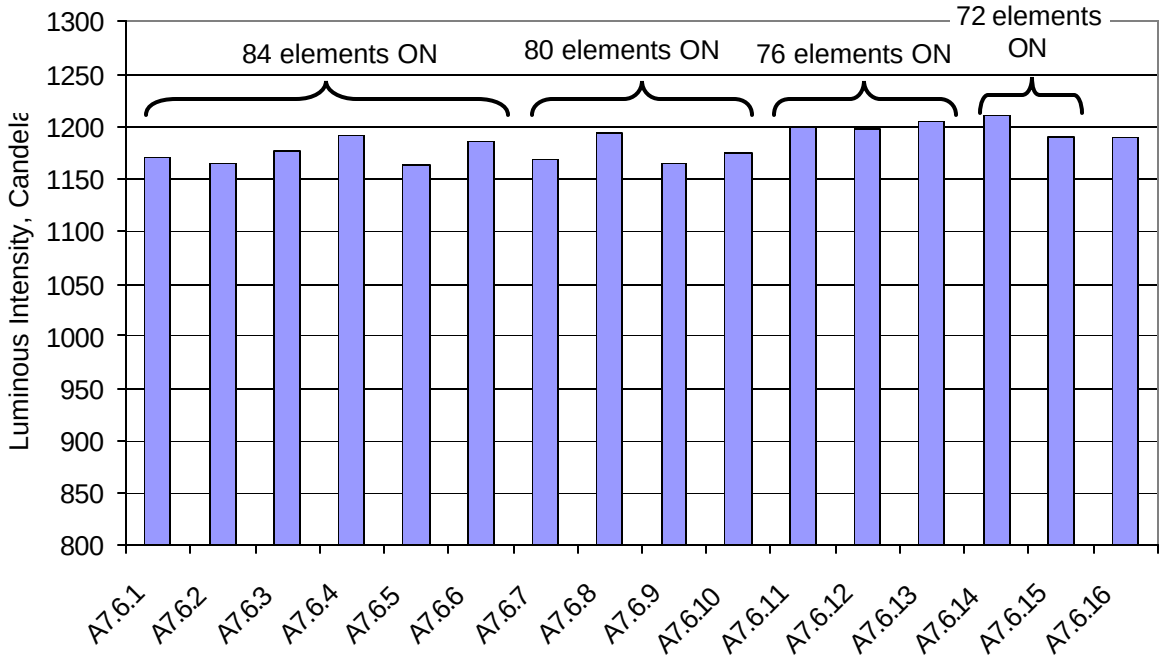

Figure 59. On-axis luminous intensity for the WPS#7 signal with different combinations of LEDs illuminated (open-circuited)

Figure 60 shows the chromaticity results from the same tests shown in Figure 59. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for red wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via open circuiting with the WPS#7 signal.

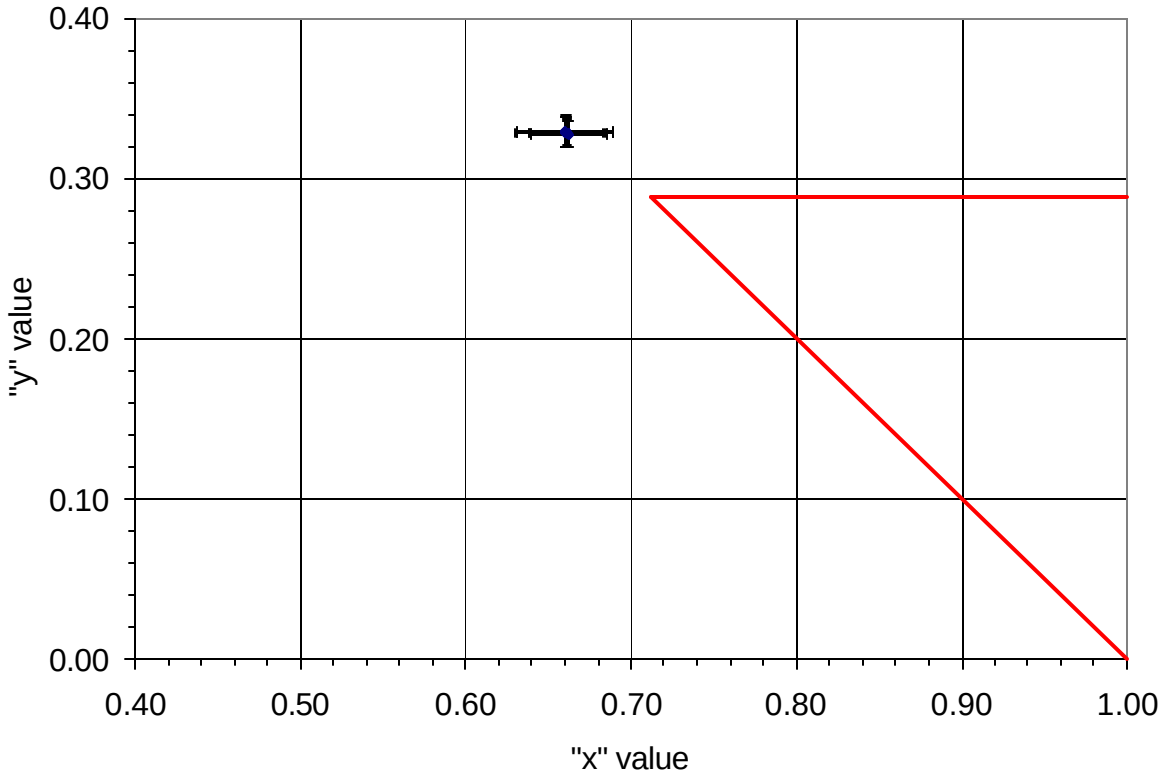

Figure 60. Chromaticity of the WPS#7 signal with different combinations of LEDs illuminated (open-circuited)

Figure 61 shows the modification to the WPS#7 signal that allows short-circuiting of individual elements. Figures A7.5.1 through A.7.5.18 of the appendix show the effects of disabling 8 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 62 summarize these results. The light output from the WPS#7 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 1215 to 1260 candela. Supply current and power consumption remained constant at 1.37 amps and 13.7 watts, respectively.

Figures A7.6.1 through A.7.6.17 of the appendix show the effects of disabling 24 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 63 summarize these results. With the exception of one anomalous data point (A7.6.8 at 832 candela), the light output from the WPS#7 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 970 to 1070 candela. Supply current and power consumption remained constant at 1.20 amps and 12.0 watts, respectively.

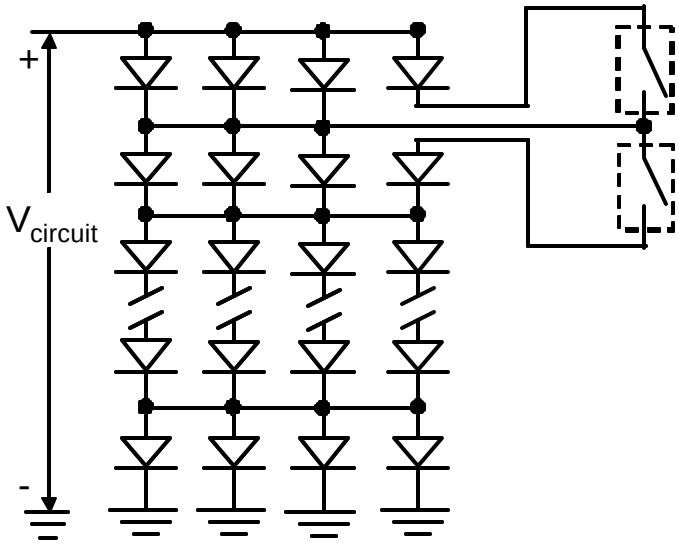

Figure 61. WPS#7 signal configured for short-circuiting

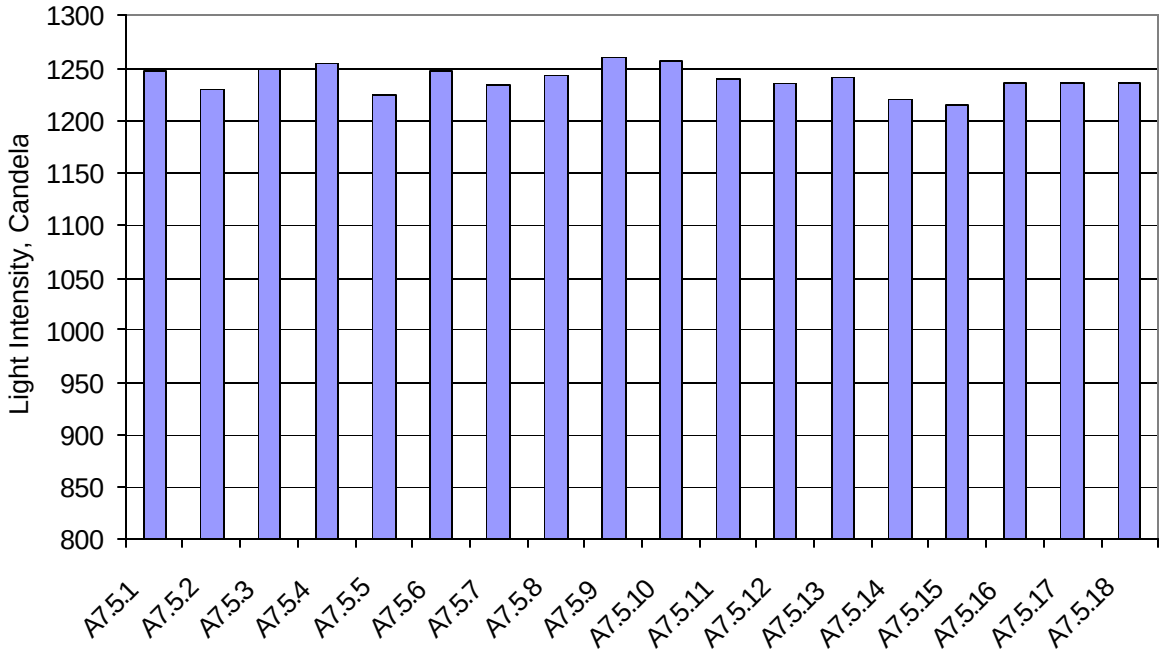

Figure 62. Maximum light intensity from WPS#7 with 80 active elements at 10.0 volts (short-circuits)

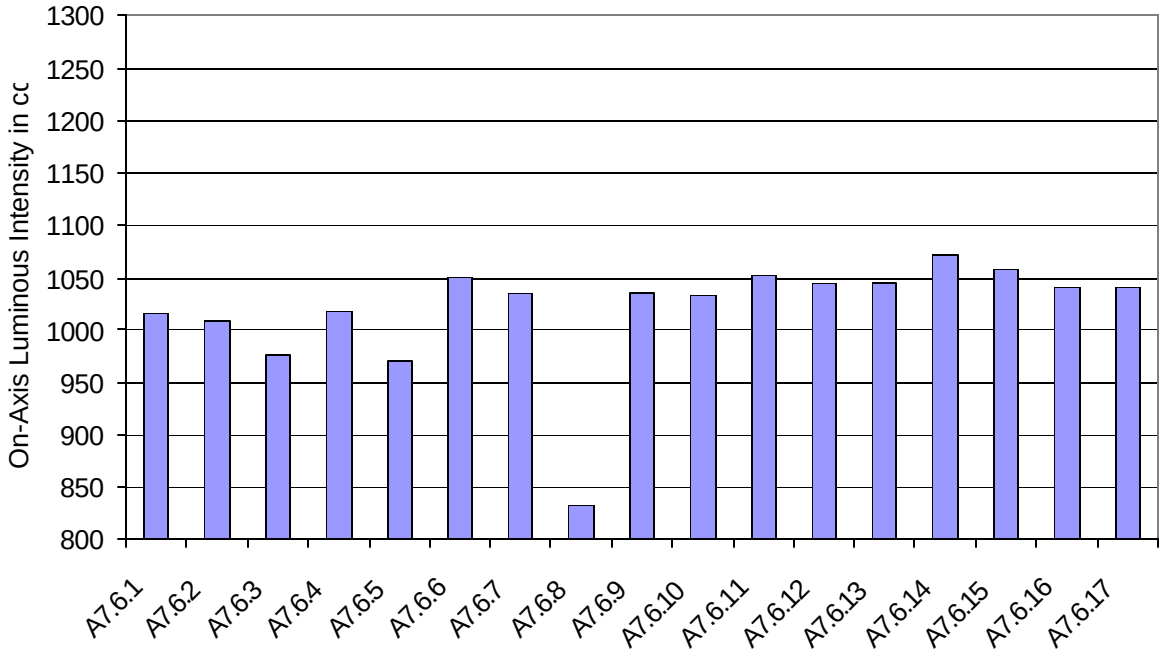

Figure 63. Maximum light intensity from WPS#7 with 64 active elements at 10.0 volts (short-circuits)

Figure 64 shows the chromaticity results from the same tests shown in Figure 62. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for red wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via short circuiting with the WPS#7 signal.

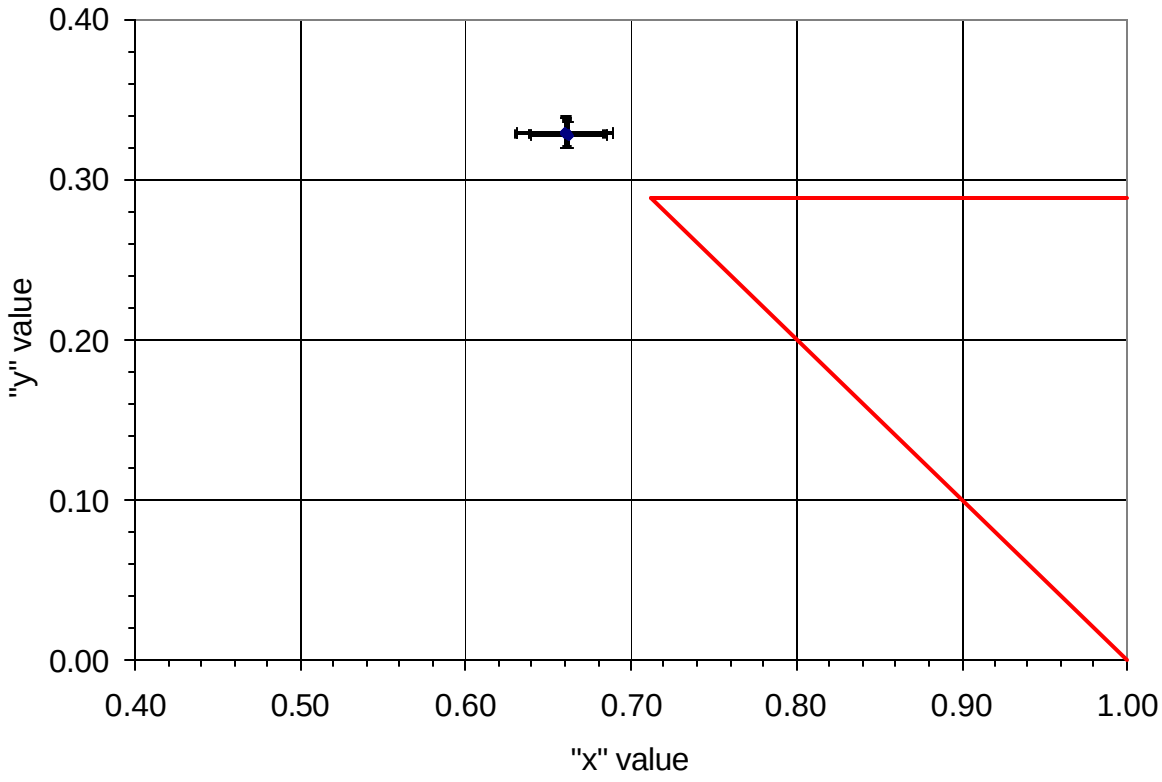

Figure 64. Chromaticity of the WPS#7 signal with different combinations of LEDs illuminated (short-circuited)

Data from Gelcore signal (WPS#8)

Figure 65 shows the configuration of the elements in a eight inch, yellow, wayside signal (#RM4 YC 85) supplied by Gelcore. This signal (referred to as WPS#8 in this report) has 88 LED elements arranged in 22 groups of 4 in a series/parallel circuit as shown in Figure 65. The WPS#8 signal uses a power supply to regulate the voltage and current applied to the LEDs. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used. This eight inch wayside signal

was equipped with a lens that gives a very narrow (~3 degree) field of view, with a claimed visible distance of 7500 feet.

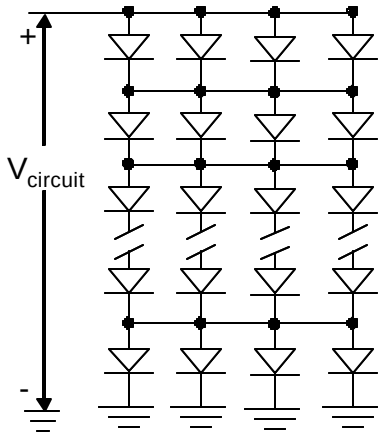

Figure 65. LED circuit configuration for WPS#8 signal

Preliminary lab testing of the three eight inch wayside signals indicated that there was a fairly strong reduction in the signal light intensity with time. WPS8b shows the uncorrected maximum luminous intensity of the three signals as a function of time. The yellow light (WPS#8) showed an almost 50% reduction from nearly 6000 candela to a steady-state value of about 3000 candela. The red light (Gelcore #RM4 RC 75) and the green light (Gelcore #RM4 GC 75) were equipped with a lens that gives a much broader (13 degree) field of view with a claimed visible distance of 4000 feet. The red light also shows a reduction in the uncorrected maximum luminous intensity, although the effect is not nearly as severe. The green light showed an almost negligible reduction in the uncorrected maximum luminous intensity as a function of time. All subsequent testing of the 8 inch wayside lights was done after “conditioning” the signal by leaving it in the ON state for 120 minute prior to testing.

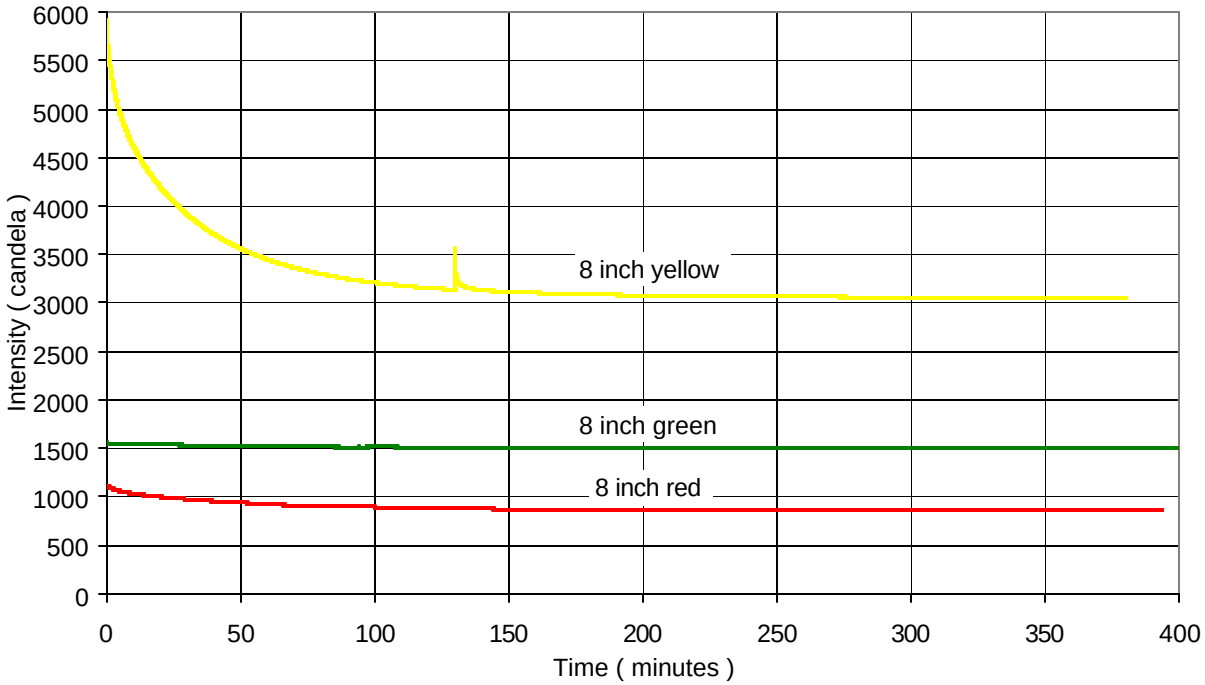

Figure 66. Uncorrected maximum luminous intensity vs. time for 8 inch wayside signals.

Figures A8.1.1 through A8.3.8 show the results of a series of tests that were conducted (unsuccessfully) to determine the point source correction factor for the yellow signal. Figure 67 summarizes the results from this series of tests, which were very inconsistent. Under ideal circumstances the output of this signal should have somewhat approximated an inverse square law. In several cases moving the signal further from the measuring colorimeter caused the maximum light intensity to increase – which should not have happened. The exact reason for the erratic behavior of this signal is unknown, but is most likely due to the narrow beam angle (~3 degrees) of the WPS#8 signal making the initial alignment much more critical than with the twelve inch crossing signals. Due to the erratic measurements of the WPS#8 signal at different distances, the point source correction was not applied to any of the readings for the eight inch signals (WPS#7, WPS#8, and WPS#9).

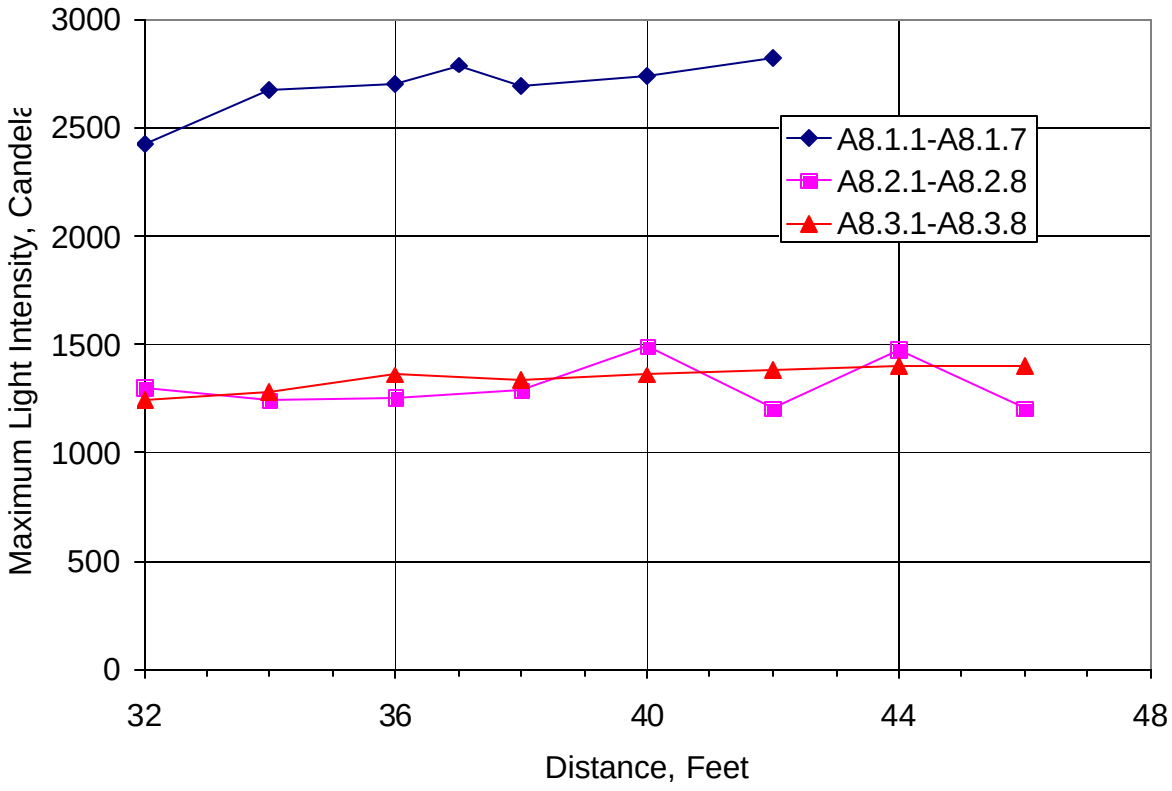

Figure 67. Maximum light intensity vs. distance for WPS#8

Figure 68 shows the circuit configuration for disabling individual LED elements via open-circuiting. Figures A8.4.1 through A.8.4.16 of the appendix show the effects of varying the number of active LED elements from 95% (84 active elements) to 77% (68 active elements) via open-circuiting at a constant 10.0 volts. Figure 69 summarizes these results. The WPS#8 signal was focused 1.1 degrees below on-axis to get the highest intensity possible. The light output from the WPS#8 signal is not a strong function of the number of active elements, with maximum outputs ranging from 1660 to 2300 candela with no apparent pattern to the results. Supply current and power consumption are essentially constant at 1.39-1.41 amps and 13.9-14.1 watts, respectively. The light-power efficiency remained relatively constant in the range of 120 to 165 candela/watt. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#8 signal. The relative insensitivity of the WPS#8 signal to the number of open-circuited elements is due to two factors:

1. the use of a power supply to regulate voltage and current, and
2. the combined series and parallel arrangement of LEDs (shown in Figure 65).

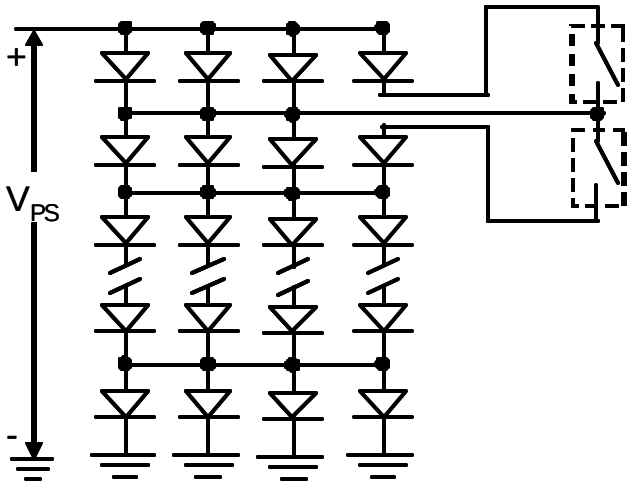

Figure 68. WPS#8 signal configured for open-circuiting

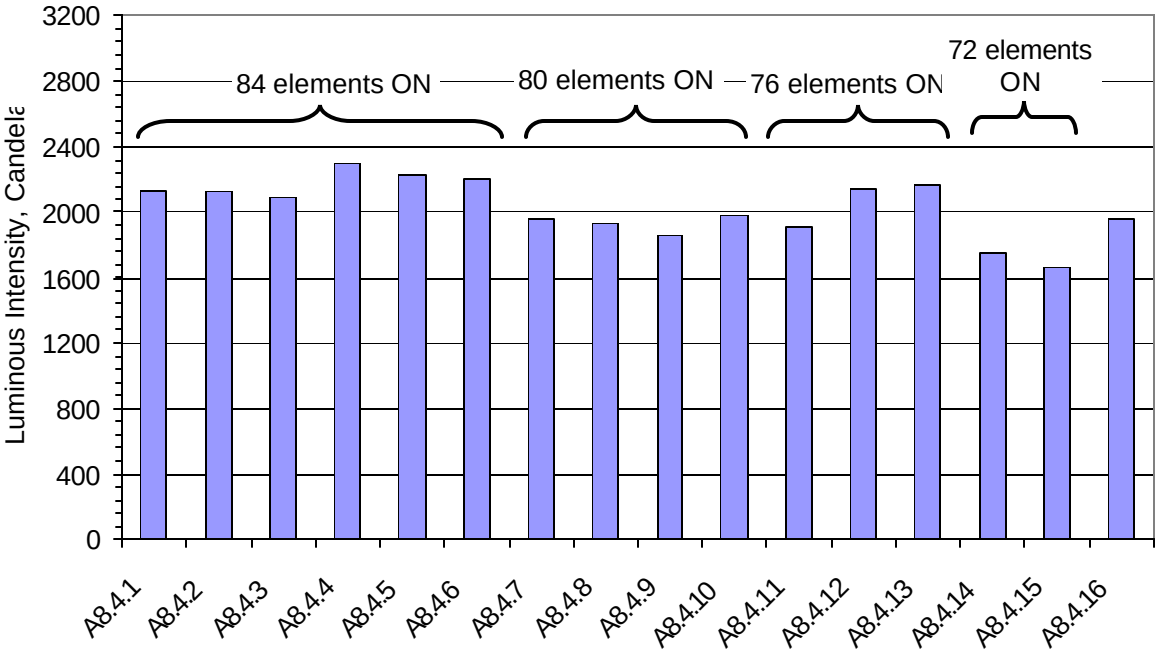

Figure 69. On-axis luminous intensity for the WPS#8 signal with different combinations of LEDs illuminated (open-circuited)

Figure 70 shows the chromaticity results from the same tests shown in Figure 69. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for yellow wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no

apparent color shift due to varying the percentage of ON elements via open circuiting with the WPS#8 signal.

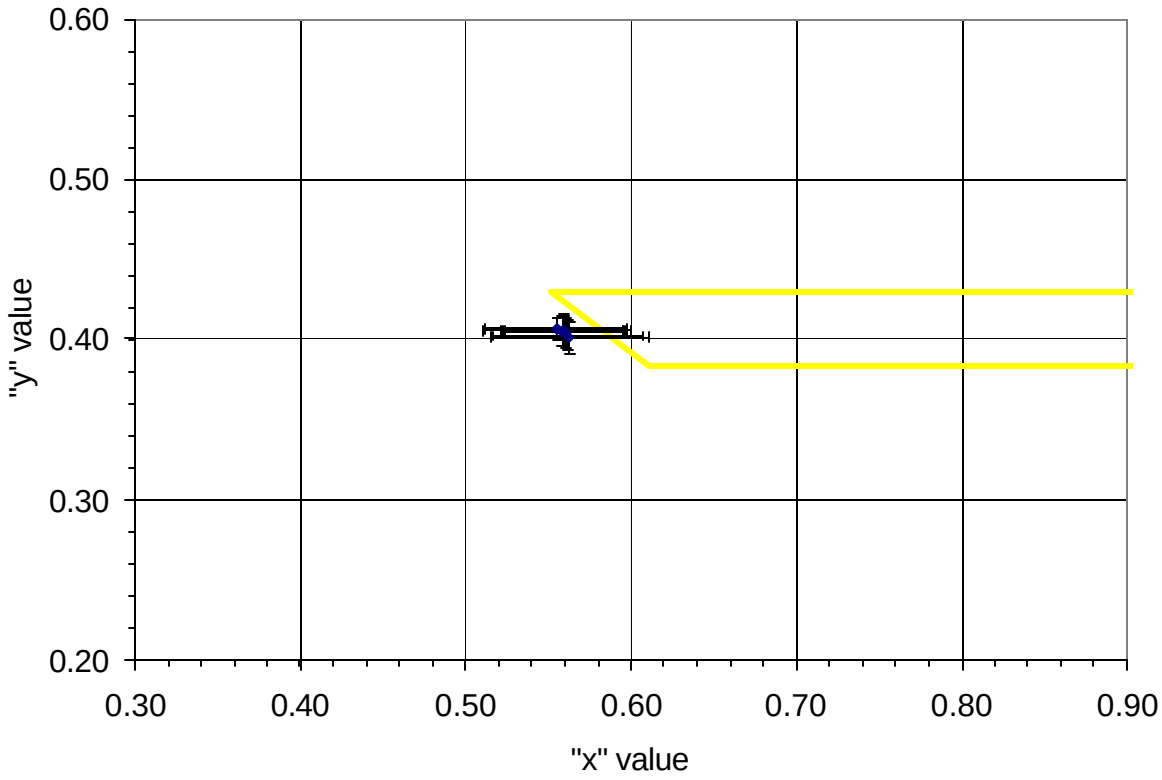

Figure 70. Chromaticity of the WPS#8 signal with different combinations of LEDs illuminated (open-circuited)

Figure 71 shows the modification to the WPS#8 signal that allows short-circuiting of individual elements. Figures A8.5.1 through A8.5.21 of the appendix show the effects of disabling 8 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 72 summarize these results. The light output from the WPS#8 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 2685 to 2856 candela. Supply current and power consumption remained constant at 1.31 amps and 13.1 watts, respectively. The light-power efficiency remained relatively constant in the range of 205 to 218 candela/watt.

Figures A8.6.1 through A8.6.21 of the appendix show the effects of disabling 24 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 73 summarize these results. With the exception of one anomalous data point (A8.6.8 at 2856 candela), the light output from the WPS#8 signal is not a function of the

particular pattern of active elements, with maximum outputs ranging over a range from 1800 to 2290 candela. Supply current and power consumption remained constant at 1.16 amps and 11.6 watts, respectively. The light-power efficiency remained relatively constant in the range of 155 to 197 candela/watt.

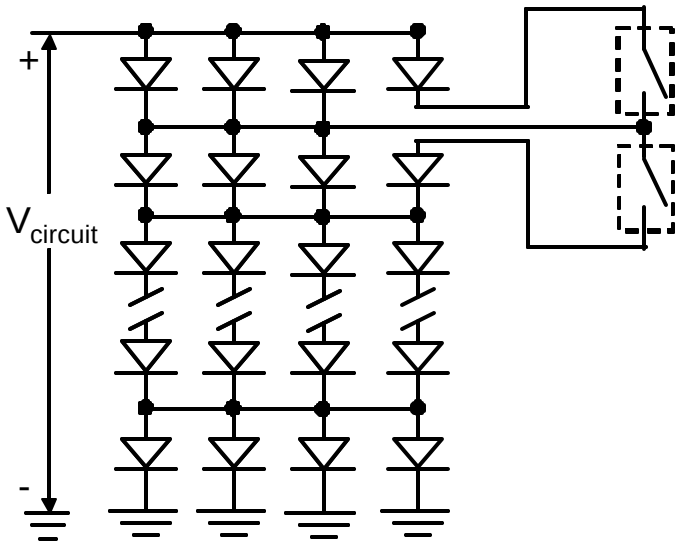

Figure 71. WPS#8 signal configured for short-circuiting

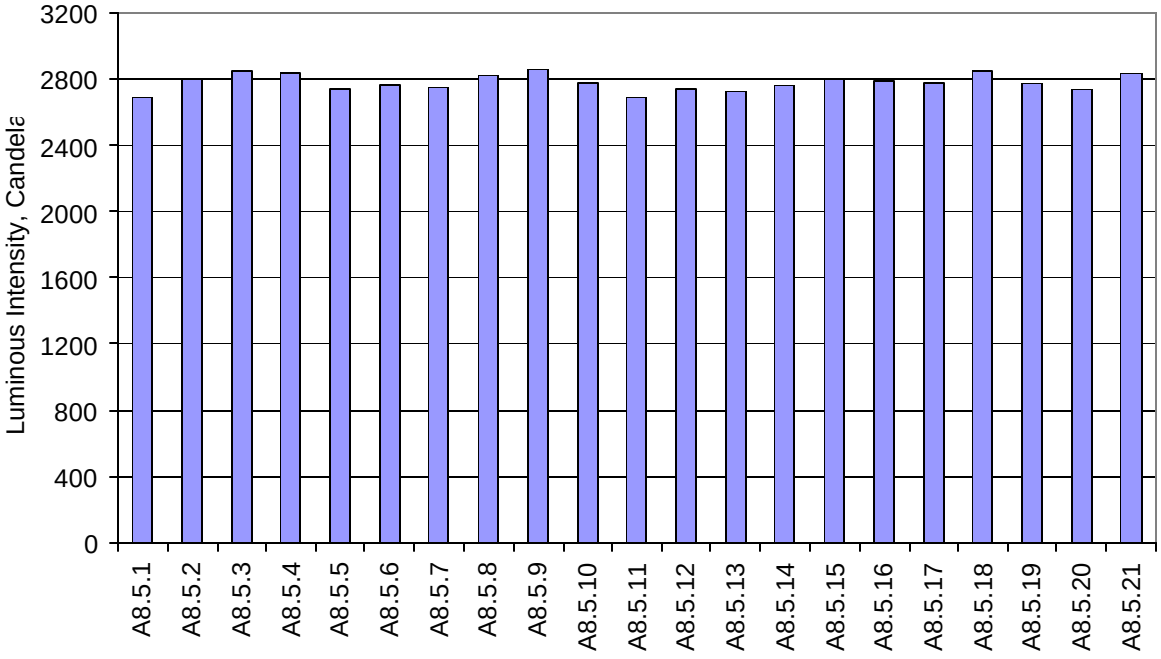

Figure 72. Maximum light intensity from WPS#8 with 80 active elements at 10.0 volts (short-circuits)

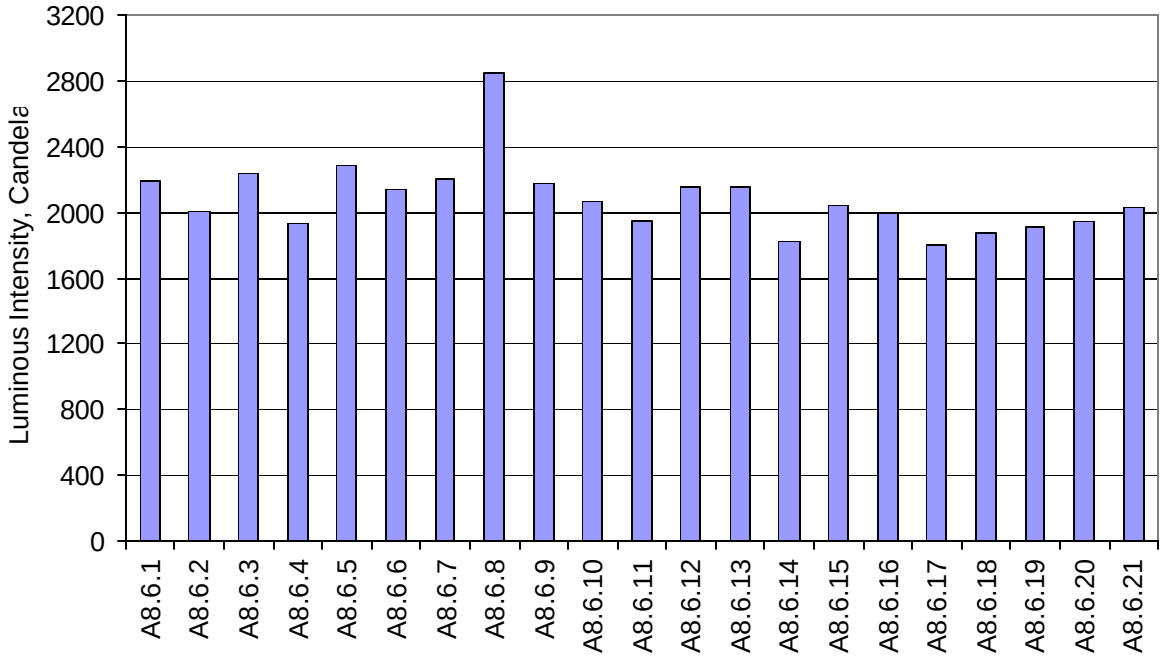

Figure 73. Maximum light intensity from WPS#8 with 64 active elements at 10.0 volts (short-circuits)

Figure 74 shows the chromaticity results from the same tests shown in Figure 73. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for yellow wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via short circuiting with the WPS#8 signal.

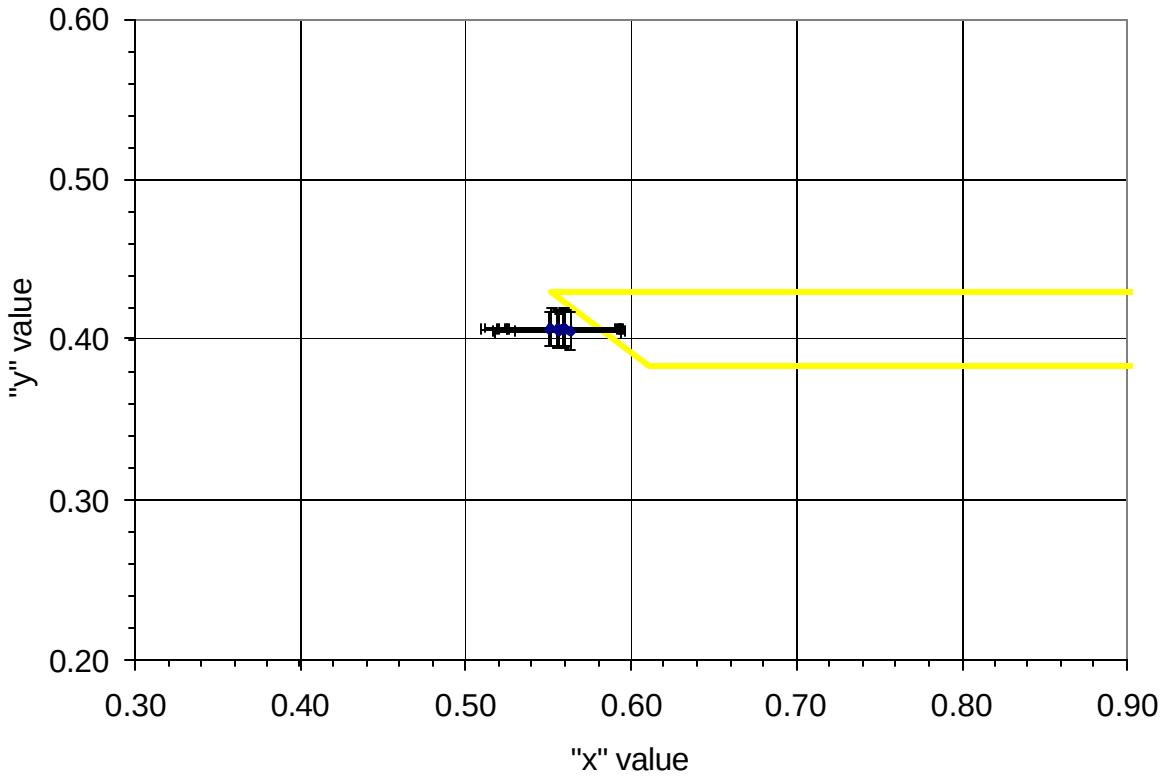

Figure 74. Chromaticity of the WPS#8 signal with different combinations of LEDs illuminated (short-circuited)

Data from Gelcore signal (WPS#9)

Figure 75 shows the configuration of the elements in a eight inch, green, wayside signal (#RM4 GC 75) supplied by Gelcore. This signal (referred to as WPS#9 in this report) has 90 LED elements arranged in 15 groups of 6 in a series/parallel circuit as shown in Figure 75. This eight inch wayside signal was equipped with a lens that gives a narrow (13 degree) field of view, with a claimed visible distance of 4000 feet. The WPS#9 signal uses a power supply to regulate the voltage and current applied to the LEDs. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

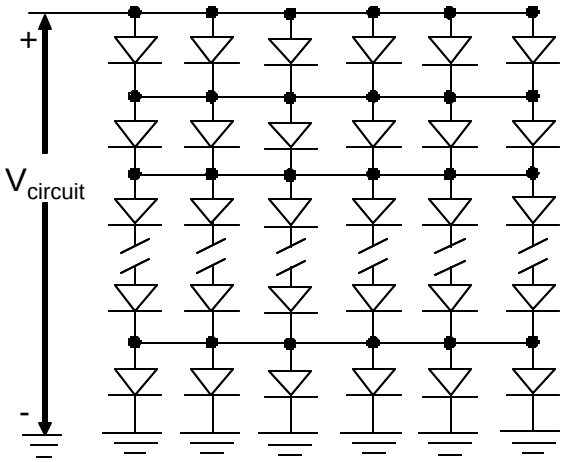

Figure 75. LED circuit configuration for WPS#9 signal

Figures A9.1.1 through A9.2.8 show the results of a series of tests that were conducted (unsuccessfully) to determine the point source correction factor for the green signal. Figure 76 summarizes the results from this series of tests, which were very inconsistent. Under ideal circumstances the output of this signal should have somewhat approximated an inverse square law. In several cases moving the signal further from the measuring colorimeter caused the maximum light intensity to remain the same or even increase, which should not have happened. The exact reason for the erratic behavior of this signal is unknown, but is most likely due to the narrow beam angle (13 degrees) of the WPS#9 signal making the initial alignment much more critical than with the twelve inch crossing signals. Due to the erratic measurements of the WPS#9 signal at different distances, the point source correction was not applied to any of the readings for the WPS#9 eight inch signal.

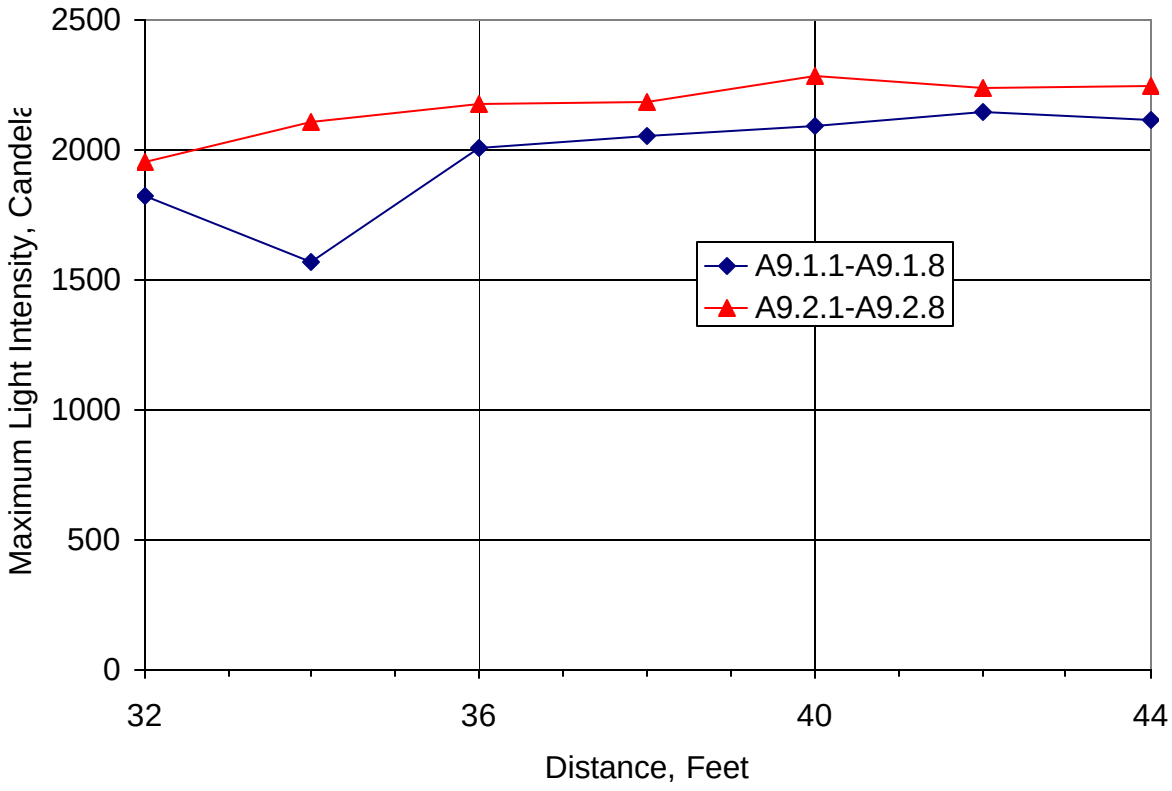

Figure 76. Maximum light intensity vs. distance for WPS#9

Figures A9.1.1, A9.1.2, and A9.1.9 through A9.1.12 of the appendix show the effects of varying voltage in the range of 8.0 volts to 13.5 volts with 100% of the LED elements active. Data from these figures is summarized in Table 25. With the exception of one anomalous reading (12.0 volts, 1505 candela), the light output from this signal is not a function of the supply voltage, with maximum outputs ranging from 2075 candela at 13.5 volts to 2055 candela at 10.0 volts. Supply currents ranged from 1.27 amps at 9.0 volts to 1.40 amps at 12 volts. Power consumption varied widely from 10.3 to 18.8 watts. The light-power efficiency was not constant, ranging from less than 100 to slightly more than 200 candela/watt.

Table 25. Results from WPS#9 with varying voltage input.

Case	Supply Voltage	Distance (feet)	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
9	8.0	38	2070	1.29	10.3	201
10	9.0	38	2072	1.27	11.4	182
1	10.0	38	2055	1.28	12.8	161
11	10.5	38	2073	1.28	13.4	154
2	12.0	38	1505	1.40	16.7	90
12	13.5	38	2075	1.39	18.8	110

Figure 77 shows the chromaticity results from the same tests shown in Table 25. All of the results show very similar color values clustered well within the AREMA limits for green wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#9 signal.

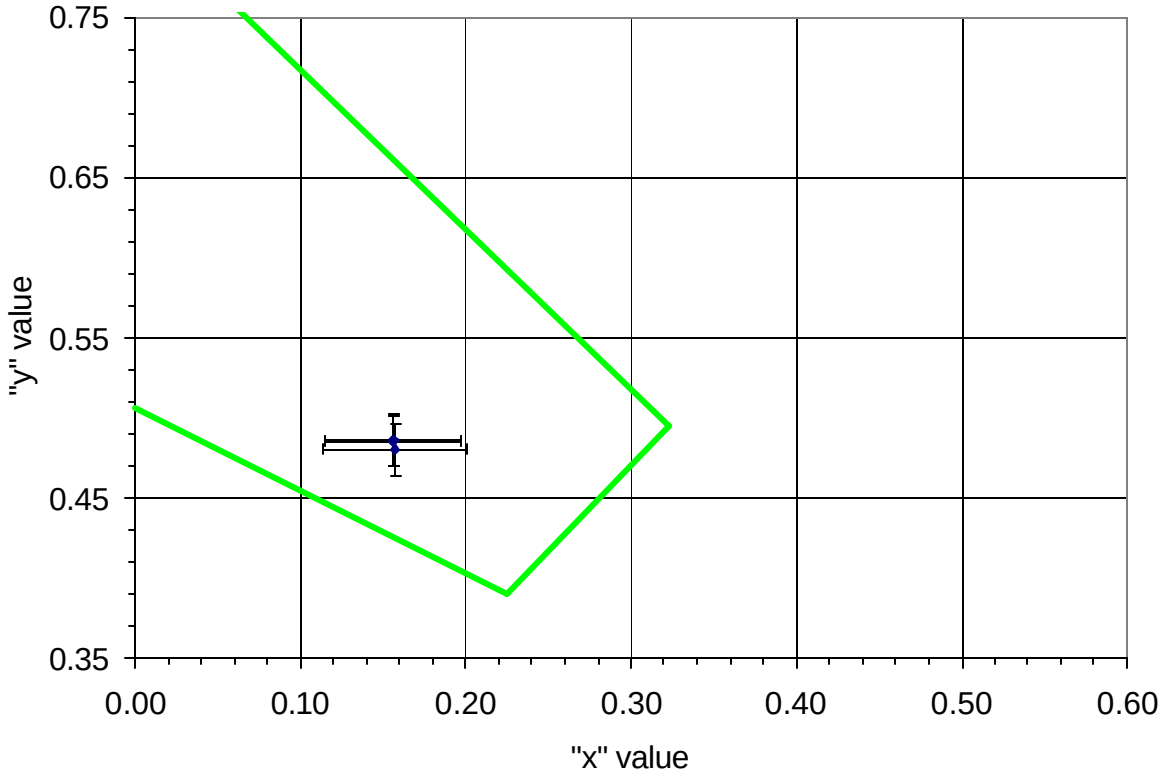

Figure 77. Chromaticity of WPS#9 with varying voltage input.

Figure 78 shows the circuit configuration for disabling individual LED elements via open-circuiting. Figures A9.3.1 through A9.3.13 of the appendix show the effects of varying the number of active LED elements from 95.6% (86 active elements) to 83.3% (75 active elements) via open-circuiting at a constant 10.0 volts. Figure 79 summarizes these results. The light output from the WPS#9 signal is not a strong function of the number of active elements, with maximum outputs ranging from 1958 to 2094 candela with no apparent pattern to the results. Supply current and power consumption are essentially constant at 1.26-1.27 amps and 12.6-12.7 watts, respectively. The light-power efficiency remained relatively constant in the range of 155 to 166 candela/watt. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#9 signal. The relative insensitivity of the WPS#9 signal to the number of open-circuited elements is due to two factors:

1. the use of a power supply to regulate voltage and current, and
2. the combined series and parallel arrangement of LEDs (shown in Figure 75).

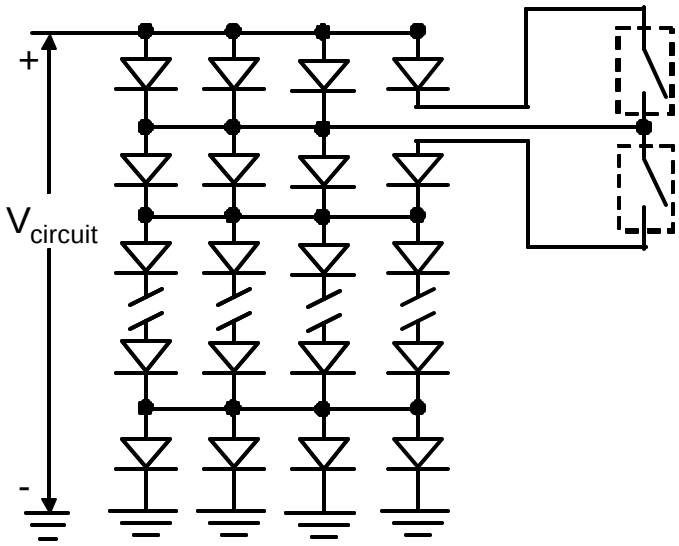

Figure 78. WPS#9 signal configured for open-circuiting

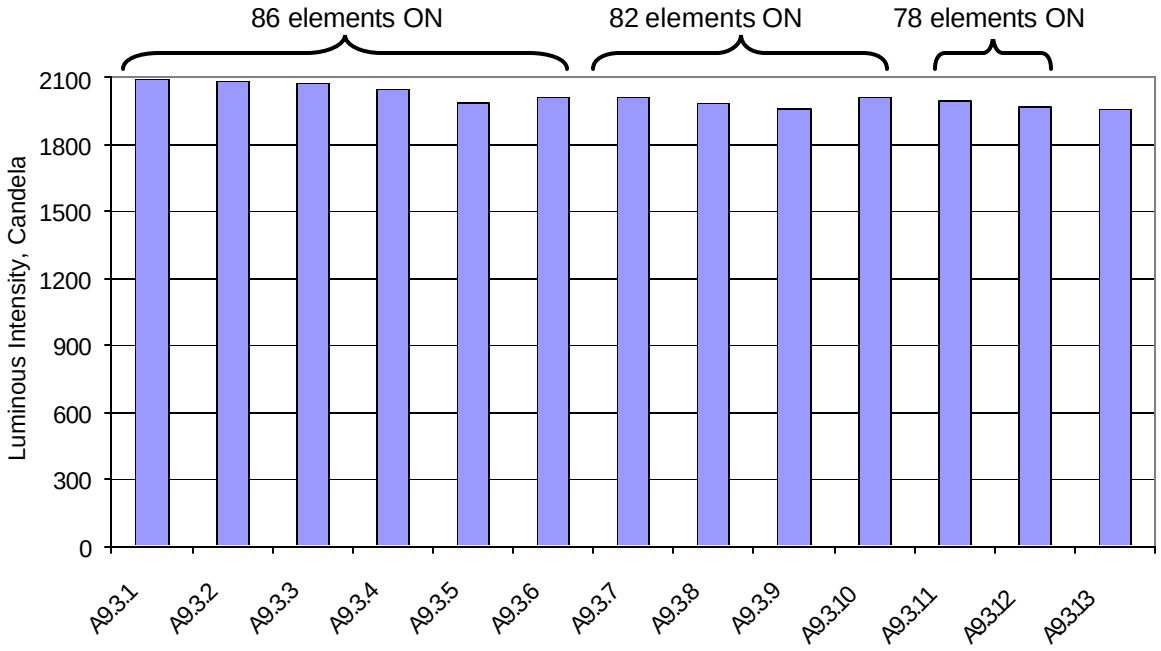

Figure 79. On-axis luminous intensity for the WPS#9 signal with different combinations of LEDs illuminated (open-circuited)

Figure 80 shows the chromaticity results from the same tests shown in Figure 79. All of the results show very similar color values clustered well within the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via open circuiting with the WPS#9 signal.

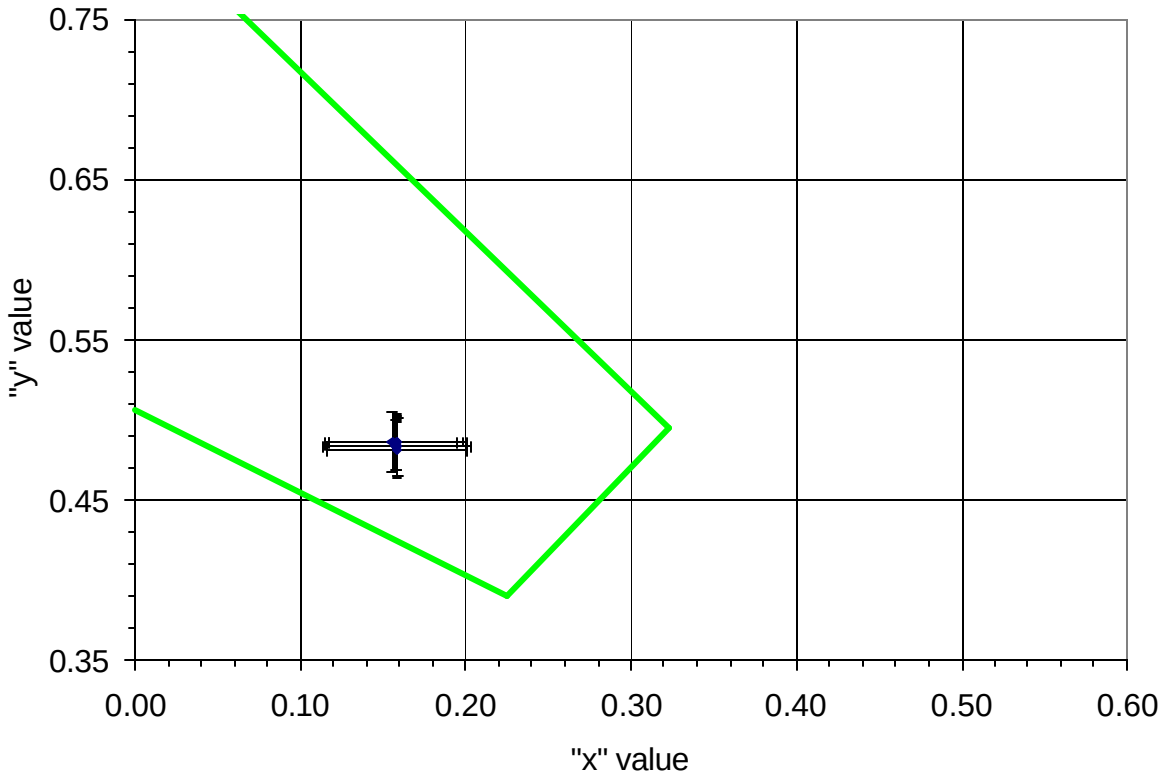

Figure 80. Chromaticity of the WPS#9 signal with different combinations of LEDs illuminated (open-circuited)

Figure 81 shows the modification to the WPS#9 signal that allows short-circuiting of individual elements. Figures A9.4.1 through A9.4.20 of the appendix show the effects of disabling 8 of the 90 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 82 summarize these results. The light output from the WPS#9 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 1614 to 1905 candela. Supply current and power consumption remained constant at 1.19 amps and 11.9 watts, respectively. The light-power efficiency remained relatively constant in the range of 135 to 160 candela/watt.

Figures A9.5.1 through A9.5.21 of the appendix show the effects of disabling 24 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 83 summarize these results. The light output from the WPS#9 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a range from 1445 to 1629 candela. Supply current and power consumption remained constant

at 1.12 amps and 11.2 watts, respectively. The light-power efficiency remained relatively constant in the range of 129 to 145 candela/watt.

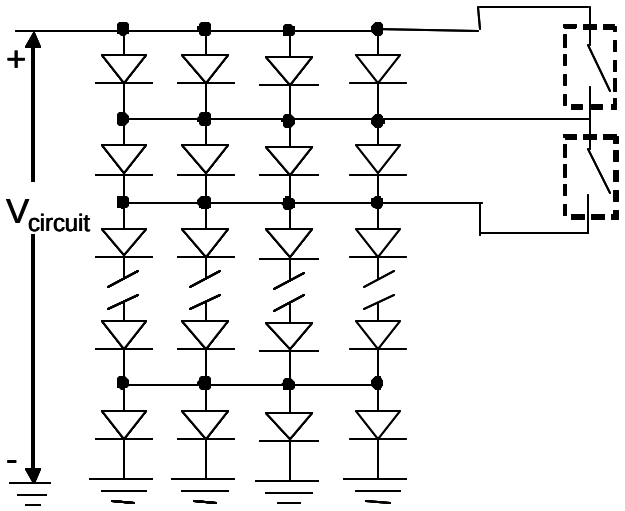

Figure 81. WPS#9 signal configured for short-circuiting

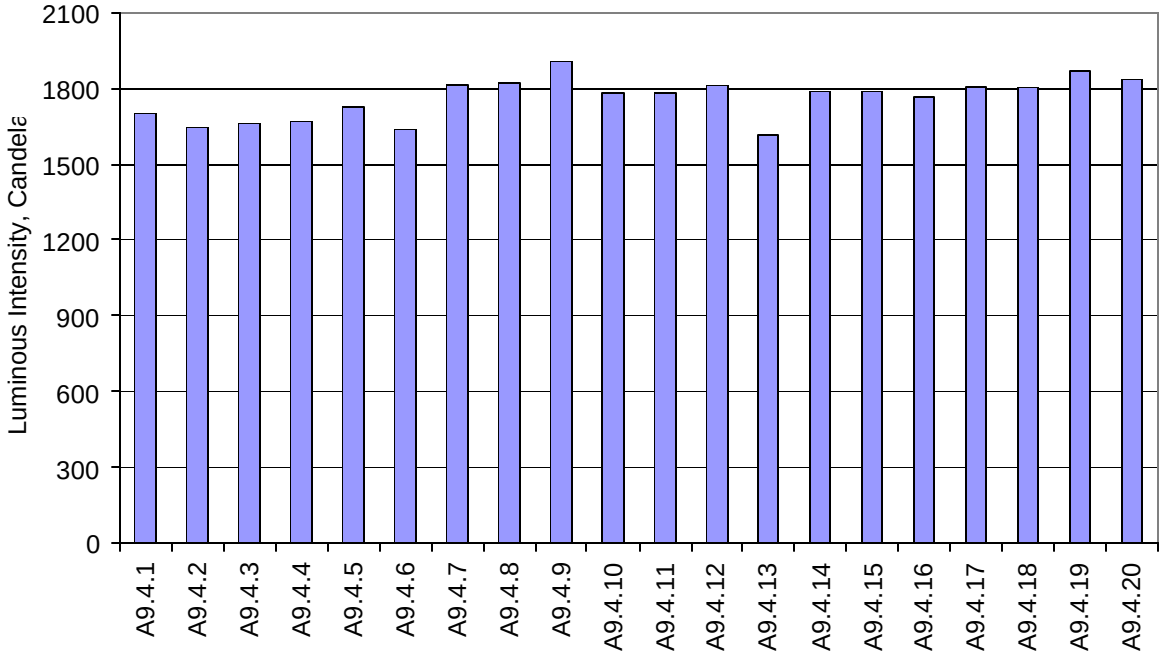

Figure 82. Maximum light intensity from WPS#9 with 80 active elements at 10.0 volts (short-circuits)

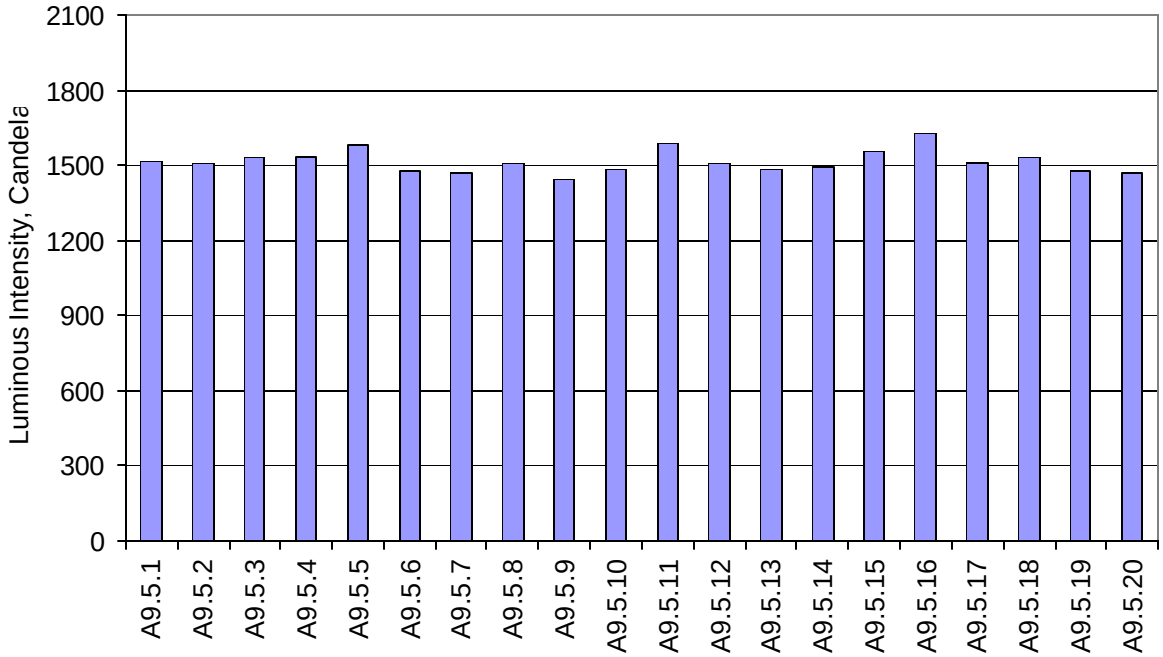

Figure 83. Maximum light intensity from WPS#9 with 64 active elements at 10.0 volts (short-circuits)

Figure 84 shows the chromaticity results from the same tests shown in Figure 82. All of the results show very similar color values clustered well within the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via short circuiting with the WPS#9 signal.

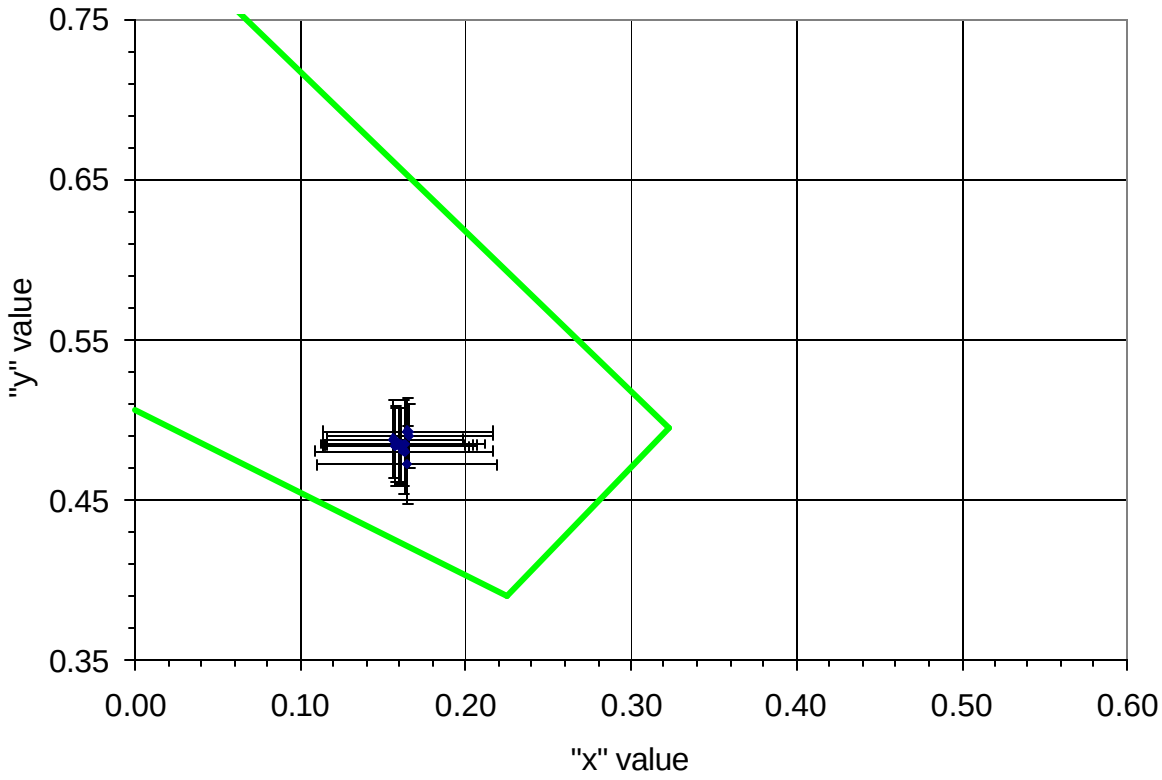

Figure 84. Chromaticity of the WPS#9 signal with different combinations of LEDs illuminated (short-circuited)